Functional Mobility Testing: Quantification of Functionally Utilized Mobility among Unsuited and Suited Subjects

Abstract:

A novel approach was used in this test for the creation of mobility requirements to be fed into the Human-Systems Integration Requirements and Engineering Requirements Documents. Existing suits may not provide adequate mobility to perform all functional tasks required in future missions. Looking solely at maximum unsuited mobility could be unrealistic and unnecessary to design into a suit. The new approach focused instead on functional range of motion. Setting design requirements based on the mobility necessary to perform a broad spectrum of functional tasks should save resources while still providing a suit capable of performing all tasks that a suited crewmember is likely to encounter. Unsuited functional mobility testing revealed some interesting nuances of human movement including variances in mobility utilized when completing functional tasks as well as the impact of compound joint motions and the influence of joint loading on range of motion. Suited requirements must reflect the fact that altered movement strategies are utilized while wearing a space suit. Improved methods for the creation of space suit design requirements should lead to improved suit performance while maintaining crewmember safety and reducing overall costs.

NASA/TP—2010–000000

Functional Mobility Testing
Quantification of Functionally Utilized Mobility among Unsuited and Suited Subjects

Scott A. England
MEI Technologies, Inc. Houston, Texas
Johnson Space Center, Houston, Texas

Elizabeth A. Benson
MEI Technologies, Inc. Houston, Texas

Sudhakar L. Rajulu
NASA Johnson Space Center

April 2010

NASA STI Program ... in Profile

Since its founding, NASA has been dedicated to the advancement of aeronautics and space science. The NASA scientific and technical information (STI) program plays a key part in helping NASA maintain this important role.

The NASA STI program operates under the auspices of the Agency Chief Information Officer. It collects, organizes, provides for archiving, and disseminates NASA's STI. The NASA STI program provides access to the NASA Aeronautics and Space Database and its public interface, the NASA Technical Report Server, thus providing one of the largest collections of aeronautical and space science STI in the world. Results are published in both non-NASA channels and by NASA in the NASA STI Report Series, which includes the following report types:

- TECHNICAL PUBLICATION. Reports of completed research or a major significant phase of research that present the results of NASA Programs and include extensive data or theoretical analysis. Includes compilations of significant scientific and technical data and information deemed to be of continuing reference value. NASA counterpart of peer-reviewed formal professional papers but has less stringent limitations on manuscript length and extent of graphic presentations.

- TECHNICAL MEMORANDUM. Scientific and technical findings that are preliminary or of specialized interest, e.g., quick release reports, working papers, and bibliographies that contain minimal annotation. Does not contain extensive analysis.

- CONTRACTOR REPORT. Scientific and technical findings by NASA-sponsored contractors and grantees.

- CONFERENCE PUBLICATION. Collected papers from scientific and technical conferences, symposia, seminars, or other meetings sponsored or co-sponsored by NASA.

- SPECIAL PUBLICATION. Scientific, technical, or historical information from NASA programs, projects, and missions, often concerned with subjects having substantial public interest.

- TECHNICAL TRANSLATION. English-language translations of foreign scientific and technical material pertinent to NASA's mission.

Specialized services also include creating custom thesauri, building customized databases, and organizing and publishing research results.

For more information about the NASA STI program, see the following:

- Access the NASA STI program home page at *http://www.sti.nasa.gov*

- E-mail your question via the Internet to help@sti.nasa.gov

- Fax your question to the NASA STI Help Desk at (301) 621-0134

- Phone the NASA STI Help Desk at (301) 621-0390

- Write to:
  NASA STI Help Desk
  NASA Center for AeroSpace Information
  7115 Standard Drive
  Hanover, MD 21076-1320

NASA/TP—2010–000000

Functional Mobility Testing

Quantification of Functionally Utilized Mobility among Unsuited and Suited Subjects

Scott A. England
MEI Technologies, Inc. Houston, Texas
Johnson Space Center, Houston, Texas

Elizabeth A. Benson
MEI Technologies, Inc.

Sudhakar L. Rajulu
NASA Johnson Space Center

National Aeronautics and
Space Administration

Johnson Space Center
Houston, TX 77058

April 2010

Acknowledgments

The authors wish to recognize several groups and individuals for their support of this test including Richard Morency, Kurt Clowers, Lindsey Turns and Andrew Abercromby for their assistance in the development of this study, personnel from the Crew and Thermal Systems Branch for their aid in testing the space suits, and the Constellation EVA Projects Office for their funding of this project.

Available from:

NASA Center for AeroSpace Information
7115 Standard Drive
Hanover, MD 21076-1320
(301) 621-0390

This report is also available in electronic form at

http://

CONTENTS

Tables

Figures

Acronyms

ABF	– Anthropometry and Biomechanics Facility
ACES	– Advanced Crew Escape Suit
EM-ACES	– Enhanced Mobility ACES
EMU	– Extra-Vehicular Mobility Unit
EVA	– Extravehicular Activity
HSIR	– Human-Systems Integration Requirements
MK-III	– Mark III Space Suit Technology Demonstrator
MSIS	– Man-Systems Integration Standards
RIDs	– Review Item Dispositions
ROM	– Range of Motion

1. INTRODUCTION

1.1 Project Overview

The purpose of this report is to summarize the findings of Functional Mobility Testing that was conducted by the Anthropometry and Biomechanics Facility (ABF) at the Lyndon Johnson Space Center of NASA. This testing was requested by the Constellation Suit Element team and funded by the Constellation EVA office.

Previous space vehicle and hardware designs were required to accommodate maximum unsuited range of motion. For example, the Space Shuttle and the International Space Station vehicle and space hardware design requirements documents such as the Man-Systems Integration Standards [1] and International Space Station Flight Crew Integration Standard [3] explicitly stated that the designers should strive to accommodate the maximum joint range of motion capabilities exhibited by a minimally clothed human subject. During the development of the Human-Systems Integration Requirements (HSIR) [4] for the new space exploration initiative (Constellation), an effort was made to redefine the mobility requirements.

Legacy design documents could be applied to space suits – leading to a requirement that suits match the mobility of an unsuited human. Based on operational and research experiences with the current space suits, such as the Space Shuttle Extravehicular Mobility Unit (EMU) and the Advanced Crew Escape Suit (ACES), as well as with prototype suits such as the David Clark suit (D-suit), the Mark III space suit technology demonstrator, and the ILC Dover Waist-Entry I-Suit (hereafter referred to as the I-Suit), it seemed that the prior expectation of maximum unsuited joint mobility would be difficult to meet, and possibly might not be necessary.

While writing the mobility requirements for the HSIR, it was decided to review and revamp the current mobility requirements. Figure 3.3.2.3.1-1 in the Man-Systems Integration Standards (MSIS, or NASA-STD-3000) [1] provides joint movement ranges for males and females. Specifically, this figure provides the 5th and 95th percentile values for various joint mobility ranges for each gender. Upon further investigation, it was determined that these values were calculated from a database of joint Range of Motion (ROM) data collected by John Jackson and Dr. Bill Thornton. These researchers gathered this data from 192 male and 22 female astronaut candidates [2]. When the results of their study were included in the MSIS, the 5th percentile value was intended to represent the most minimum and a 95th percentile value the most maximum motion as observed within either the male or the female sample population. However, the way these values are portrayed, it could be misconstrued that a small female/male has a limited range of mobility when compared to a large female/male. In reality, it is quite likely that a large male with large muscle mass would end up having less range of motion than a short, thin male who has a high flexibility in his joint range of motion.

Designers and engineers, despite adequate information about this discrepancy, may still have difficulties with either a) trying to enable different sizes of people with different ranges of joint motion to accomplish a task or b) trying to figure out which joint limit number out of 4 numbers (5th and 95th for males and females) to choose for a specific task. To avoid these issues, it was decided to review the 5th percentile male and female data and use the smallest of these values as the minimum unsuited mobility requirement. The HSIR currently states these as the minimally necessary mobility range requirements for unsuited and suited operations. It should be noted that even though suited data was not available at the time, extension of unsuited mobility to suited mobility stems from the existing stipulations in previous space vehicle design requirements. The philosophy behind continuing with the previous stipulation was that the provided values would then be a very conservative estimate of range of motion, one which any crewmember would very likely be able to achieve.

After the HSIR was published for designer consumption, Review Item Dispositions (RIDs) were written against the minimum mobility requirements. The RIDs were submitted to ascertain that these were indeed the minimally necessary joint range of motion values to be levied against suit design, and to determine if a suited crewmember would actually need this full range of motion to complete all required functional tasks.

The idea behind using functional range of motion instead of maximum ranges of motion is based on the contention that the functional range of motion should, in general, be less than even conservative estimates of maximum range of motion currently in the HSIR. This could in turn result in more relaxed suit and vehicle design requirements.

However, as was found in this project, the minimum range prescribed in the current HSIR document is generally conservative compared to what is possible maximally, as well as what is minimally needed to perform all necessary functional tasks. Hence, during the mid course of this test, the subjects' isolated joint range of motion data was gathered, as a way to demonstrate that what is being prescribed for functional task capabilities is not a replica of maximum range.

1.2 Literature Review

Unsuited Literature Review

A limited range of motion is often a symptom of joint pathology, and an operator's range of motion is an important factor to consider when designing a mechanical system, so there have been numerous studies of human range of motion. These studies have been joint-specific (e.g. only measuring the hip joint) or more comprehensive, utilizing subject pools ranging from one to hundreds, and using an entire suite of possible measuring devices. Some characterize the differences in ROM associated with age and gender, while others sort range of motion based on body type (thin or athletic, for example).

While most recent studies have involved the testing and verification of measurement methods, or have been concerned with determining the range of motion of one particular joint, older studies were more comprehensive, and concerned with determining the general mobility of a human.

One of the more comprehensive studies was conducted in 1955 by Dempster, and was reanalyzed by Barter, Emanuel and Truett in a 1957 paper [5]. The data was collected by analyzing photographs of 39 men, with an average age of 21.1 years. Dempster's data was subdivided based on the physique of his test subjects (thin, muscular, median and rotund). Barter, Emmanuel and Truett performed a statistical analysis to quantify the effect of physique on mobility, and determined that this effect was small enough that the mobility ranges could be presented as an average across all subjects. The authors indicated that Dempster's study was one of the more comprehensive available at the time, as well as providing detailed information on how measurements were taken. The reduced data presented by Barter, Emmanuel and Truett is referenced by Occupational Biomechanics, a text by Chaffin, Anderson and Martin [6].

Another study, done in 1979 by Boone and Azen, [7] attempted to correlate the mobility of subjects with their age. One hundred and nine male subjects were measured using a goniometer. A goniometer involves two straight edges that can rotate relative to a protractor, against which the angle between them is measured. Most of the measurements were taken with the subject in a supine position, but the subject was prone for extension of the shoulder and hip, and seated for hip rotation. One experimenter took all of the measurements, to exclude the measurement differences that would occur between testers. One of the strengths of the Boone study is the large number of subjects (56 males over the age of 19). The biggest concern with using the results is a lack of detailed information on how the joint rotations were defined.

Motions such as shoulder abduction and hip rotation have had different interpretations in various studies, making comparison difficult without further information.

Another source of mobility data is a military text, MIL-HDBK-759C [8]. This book, the Handbook for Human Engineering Design Guidelines, is meant to be a reference for designers. Minimum, maximum and average values are provided for each type of motion. The handbook includes an image showing each motion, but does not provide any information on the number, gender or size of subjects. Therefore, the published values should be regarded with some caution. The measurement methods are as described in Barter, Emmanuel and Truett [5].

Yet another general mobility study was conducted by N. Doriot and X. Wang, as described in their 2006 paper [9]. They examined 41 subjects: 22 young (aged 25 to 35) and 19 elderly (65 to 80). Their subject pool consisted of 21 men and 20 women. The study's aim was to measure maximum voluntary range of motion for all of their subjects, and then discern the influence (if any) of age and gender on mobility. Their study was limited to joints of the upper body (shoulder, torso, etc.) To avoid forcing their subjects to hold a posture as they were measured, the authors chose to use motion capture techniques, instead of the traditional static goniometry used to gather data for most studies.

By their definition, a joint was required to reach its maximum without 'direct assistance,' meaning that the subject could not, for instance, press their hand against a flat surface to induce wrist extension. All motions were performed while the subject was minimally clothed, secured by a lap belt in a chair without a seat back. Reflective markers were affixed to the subject (glued to the skin, or attached to a formfitting gym suit), and tracked using a VICON motion capture system. One of the study's limitations was the method in which the subject was restrained. A lap belt secured them to a stool without a back, and they were instructed to perform all motions with their hips against the chair. The chair did not appear to be fixed to the ground, so any kind of off-axis movement could lead to feelings of instability, which might restrict the subject's comfortable range of motion. For example, it seems unlikely that the subject would want to lean very far back (torso extension), given the possibility that the chair could tip backwards with them. The authors report the apparent decrease in mobility with age, by examining maximum joint angles achieved while moving the upper body. They suggest that the amount of degradation is specific to both the type of joint, and the type of motion attempted by the joint. For instance, their data suggests that maximum neck flexion does not decrease as much as neck extension. However, it should be kept in mind that these were maximum voluntary movements, meaning that the subject had some control over how far they pushed themselves. Younger subjects could easily be more aggressive in their movements than older, more guarded subjects.

As can be seen from even this small cross section of mobility studies, there are several methods to measure joint range of motion, each with associated limitations. Studies have varied in their measurement tools, their techniques, and even in their definition of joint motions.

For example, Boone and Azen [7] used a goniometer, which must be aligned with physiological landmarks on the subject. Due to the subjective nature of this alignment, there could be differences in measuring technique between experimenters, or even between different tests by the same experimenter. Barter, Emmanuel and Truett [5] measured joint angles from photographs, another subjective method. An inclinometer can be used to measure trunk mobility (as seen in Kachingwe and Phillips [10]), but its accuracy can be affected by initial misalignment, or slipping where it is affixed to the subject. Motion capture data, as seen in Doriot and Wang [9] and the current study, can be a less subjective tool than goniometry or photography, but there can be relative shifting or occlusion of the markers that are used to track motion.

In addition to the variety of measurement tools that can be used to study range of motion, there can be a great deal of variance in the measurement method (even beyond the placement of a goniometer). These variations can lead to large differences in reported data, and can limit the ability to compare data from multiple studies. For example, some studies involve a freestanding subject (Chang [11]), while others force the subject to remain seated (Doriot and Wang [9]) or lying down (Boone and Azen [7], except for hip rotation). Many studies assist a subject in reaching their physiological limits, by allowing them to press a limb against a static surface, as in flattening their palm against a tabletop.

Finally, there can even be differences in the notation that is used to describe joint rotation. For example, Boone and Azen [7] describe "Horizontal Extension" and "Horizontal Flexion" of the shoulder. In the current study, this motion would be described as shoulder abduction/adduction. In the MSIS [1], shoulder abduction/adduction is a completely different motion, which involves swinging the arm in a horizontal (transverse) plane, level with the shoulder. If these potential distinctions in notation were not kept in mind, it would be easy for a researcher to erroneously compare range of motion values for very dissimilar motions.

Suited Literature Review

In addition to the multitude of investigations on minimally clothed range of motion, there have been several studies on how protective clothing affects mobility. A common method of assessment involves measuring angle sweeps from photographs, often in front of a grid with a known scale - for instance, taking a photo of the subject in their neutral position, and another photo when they have moved a joint to its limit (see Figure 1 for an example).

Figure 1: Example of Grid for Motion Analysis [12]

Some concerns with this method include the skewing of apparent angles when views are not purely orthogonal, and difficulty in applying this method when subjects are attempting anything besides purely isolated motions. For instance, if a subject is performing complex motions such as egressing a seat, it may be very difficult to pull accurate joint angles from a photograph.

Two studies on clothed range of motion include a dry suit mobility study [13] and an assessment of how cold weather clothing restricts the wearer [14], both done using a photographic method. In the second study, a rudimentary motion analysis system was used to track markers that were affixed to the subject.

From the beginning of space suit development there have been attempts to quantify the mobility of a space suit, beyond purely subjective evaluation. A paper by John Roebuck in 1968 [15] discusses the difficulties associated with quantifying space suit mobility, and suggests methods for evaluating the Apollo suits. He mentions the lack of standardization in biomechanical terms (abduction, adduction, flexion extension, etc.) across different fields, and proposes a system that could quantify mobility in terms that an engineer could understand. Although the final result is perhaps more confusing than conventional terminology (perhaps this is why it has never been adopted), he does bring up several interesting points that relate to the current study. For instance, he discusses the isolation of one segment from another through the use of a bearing, and the resulting exaggeration in relative rotation, compared to the same measurements of human subjects. For instance, the 'forearm' of a suit is connected via a bearing to the glove – so the glove can rotate freely with minimal rotation of the forearm. In a human, rotation of the hand is accomplished through rotation of bones in the forearm, meaning that the relative rotation between the two segments can be minimal. He also brings up the limitations that can occur when a suit designed for pressurized operation is worn unpressurized. Finally, he mentions that a study of suited mobility should ideally be combined with a study of torque vs. range of motion.

Another early attempt at quantifying space suit mobility was the use of time and motion studies [16] to determine mobility data from Apollo lunar EVAs. Analysts determined data such as mobility rate and stride length from video, often using the known crewmember height as a scale factor. Metabolic rate data was introduced in an attempt to quantify the amount of work being done by the astronauts - for instance, to compare the efficiency of different modes of translation. Interestingly, the two crewmembers sometimes chose different methods to cover the lunar terrain: the commander of Apollo 16 'walked' while the Lunar Module Pilot (LMP) tended to 'hop.' A "Vanguard motion analyzer", a device that allowed projection of video onto a glass plate, which could be overlaid with graph paper for marking frames, was used to evaluate motion during falls on the lunar surface.

The calibrated grid method was one of the techniques mentioned in a 1992 JSC paper [17], which discusses the evaluation of three space suit technologies as potential space station suits. The Ames AX-5 hard suit, the zero-prebreathe MK-III, and the Shuttle EMU were all examined for their mobility characteristics, in addition to other factors such as maintainability and comfort. The mobility assessment involved studies in the Weightless Environment Training Facility (WETF), runs on the KC-135 (an aircraft flown by NASA to allow short periods of microgravity during parabolic flight), and an unmanned component evaluation that included both range of motion and torque. WETF work included 'mobility exercises such as lower torso bending and torso rotation' [17, p.1218] in front of a clear mobility grid, as video was taken. Elbow flexion was measured by placing a protractor on the suit's elbow mobility joint. Unmanned component evaluation involved measuring the torque developed by moving a joint through its range of motion, and also examined the torque required to hold the joint at a series of positions. Although this study could be helpful in comparing different joints, the data may not directly apply to suited humans, since man-in-the-loop testing suggests that torque values are higher when a human is inside the suit, and it is also likely that a suit's range of motion will be impacted by interference with a human inside.

A 1999 study by ILC Dover [18] compared three space suits: the Apollo A7LB, the Shuttle EMU, and an ILC Dover Waist Entry I-Suit. A set of isolated joint motions were performed in front of a grid, and photographic transparencies were overlaid to determine how far each joint had been rotated from its initial position. The study also involved a set of functional tasks, during which a set of mobility parameters (maximum step height, walking speed, etc.) were collected to supplement qualitative evaluation.

2. METHODS

2.1 Experimental Design

A novel approach was used for the creation of design requirements in this test. Current suits may not provide adequate mobility to perform all functional tasks required in future missions. Looking solely at maximum unsuited mobility could be unrealistic and unnecessary to design into a suit. The new approach focused instead on functional range of motion. Setting design requirements based on the mobility necessary to perform a broad spectrum of functional tasks should save resources while still providing a suit capable of performing all tasks that a suited crewmember is likely to encounter. Figure 2 illustrates a comparison of hypothetical maximum isolated and functional range of motion (ROM) as was hoped to be developed by this test. To the author's knowledge, this approach for the creation of suit requirements had never been attempted.

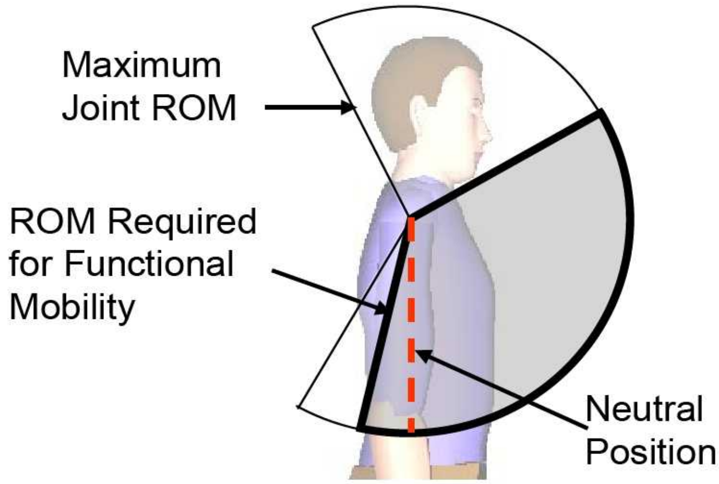


Figure 2: Theoretical Isolated vs. Functional Mobility

Functional Task List

A list of all tasks likely to be performed by a suited crewmember through all phases of launch, flight, and reentry was generated (Appendix A). This list was then pared down for brevity into a smaller list of major functional tasks that should encompass the maximum range of joint mobility (Appendix B). Efforts were made to avoid redundant tasks, minor tasks, and tasks that would likely be exceedingly difficult or impossible to collect with existing motion capture methods. Examples of redundant tasks include multiple permutations of hand tool usage unlikely to result in significantly different joint angles. Examples of minor tasks include tasks that are highly unlikely to maximize any joint angle, such as button pushing or toggle flipping. Examples of difficult tasks to collect include moving from supine to standing postures such as in a fall recovery, where reflective markers would be highly occluded and likely knocked off. The breadth of tasks being collected should resolve any potential gaps left by avoiding certain highly obtrusive tasks.

2.2 Data Collection

All unsuited data was collected over a three-month period in the Anthropometry and Biomechanics Facility (ABF) at NASA's Johnson Space Center. Suited data was collected over the following 6 months based on suit and subject availability. Kinematic data was recorded at 200 Hz with a Vicon 612/SV

(Oxford Metrics, Oxford, UK) passive video-based motion analysis system containing 10 cameras for this study. Forty-one retroreflective markers were placed at various points on the unsuited subject with at least 3 points per major body segment to enable the calculation of major joint angles (Figure 3). Suited marker sets were similar to the unsuited marker set with slight modifications required to accommodate the varied suit architectures.

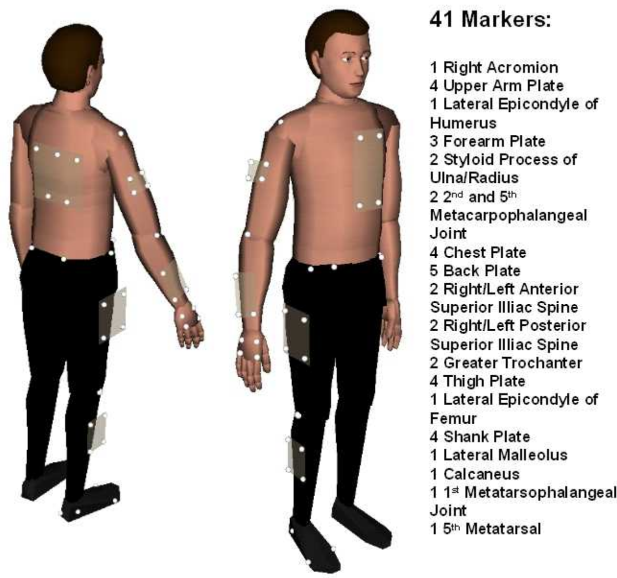


Figure 3: Retroreflective Marker Set & Anatomical Landmarks

A variety of props (Figure 4) were used during the performance of the functional tasks. These props included a hammer, an empty box, non-rolling desk chairs, a safety ladder, a recumbent seat, and a Primus RS (BTE Technologies, Hanover, Maryland) system. The Primus RS system is typically used for evaluation of subject strength, but its functionally oriented design makes it a simple replacement for a large array of props (Figure 5).

Figure 4: Some Utilized Props

Figure 5: Primus Attachments

For the unsuited test, 20 healthy subjects were used, 10 males and 10 females, who were required to be healthy enough to perform the tasks and free of any major joint pathologies which might restrict range of motion. Four additional subjects were later added to the test subject pool, and completed unsuited testing to provide a baseline to compare to their suited tests. The suited tests subjects all completed testing in both the pressurized and unpressurized state of the suit they were brought in to test, with the exception of the MK-III in which testing was only completed in the pressurized condition. Four subjects were tested in each of the suits. It should be noted that due to subject availability, subjects were not always replicated across suits. Specifically, three subjects tested in two of the suits, one tested in three of the four suits, two subjects tested in only one suit, and one subject completed testing in all four suits.

A chief concern during video motion capture is the ability to collect data truly representative of the tasks being performed. To this end, subjects were asked to wear skin-tight clothing for the unsuited test to enable optimal placement of the retroreflective markers. Once subjects were instrumented with 41 markers, a single laser scan using a Vitus Smart 3D Full Body Scanner (Weisbaden, Germany) was also taken of the subjects to allow for extraction of any desired anthropometry at a later date. The subjects then performed 49 functional tasks while data was collected for each trial. The functional tasks performed by the suited subjects differed in several ways from the functional task list performed by unsuited subjects in the interests of safety and the logistics of moving in a suit. Some tasks could not be performed while others had to be substantially modified based simply on the characteristics of the inspected suits, including weight, fit, comfort, and pressurized mobility. Some of these trials were repetitive to accommodate high frequency of marker occlusions or to allow for symmetry, since markers were only placed on limbs on the right side of the body. Subjects were instructed before each trial concerning the task they would be performing next. If issues occurred such as a marker falling off, the trial was repeated. After functional data was collected, isolated mobility data was gathered as subjects maximized principal motions of each major joint about every axis sequentially. The data was intended to quantify the mobility required to perform all functional tasks as a fraction of total mobility available, and also to compare average population ROM to accepted values from literature.

Joint angles were calculated by assigning a coordinate frame to every major body segment and comparing the relative rotation of distal segments about their proximal segments. Angle calculations were performed in Vicon BodyBuilder software (Oxford Metrics, Oxford, UK) and measured in each primary axis of the body. For example, shoulder flexion/extension was calculated by rotating the X-axis of the upper arm segment about the X-axis of the torso. The positive X-axis extends out of the body to the right in the neutral position; therefore, shoulder flexion is reported as a positive value since it represents a positive rotation about the X-axis. This convention holds for all major joint calculations, and can be seen in Figure 6.

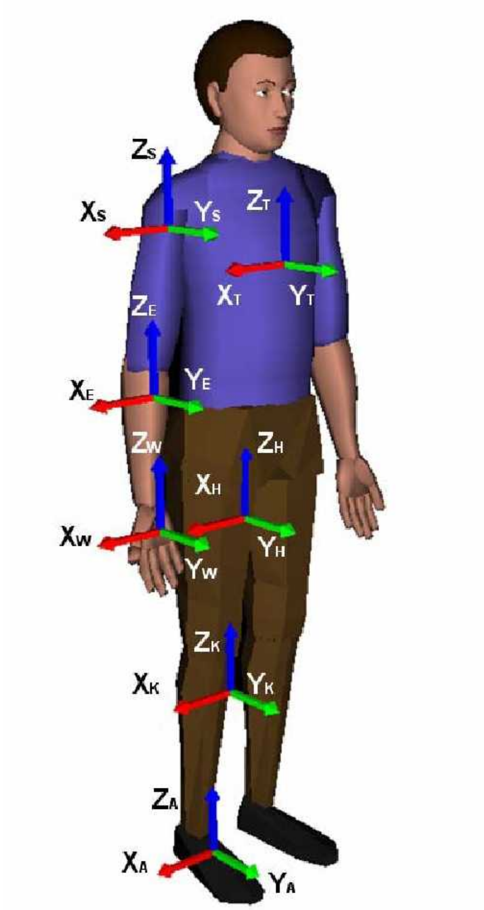


Figure 6: Coordinate Frames attached to the Body

Table 1 below shows the joint angle definition that was used in this study.

Table 1: Definition of Joint Rotations

Joint Rotation	Axis of Rotation	Child Segment	Parent Segment
Shoulder Flexion/Extension	X_S	Upper Arm	Torso
Shoulder Abduction/Adduction	Y_S	Upper Arm	Torso
Elbow Flexion/Extension	X_E	Forearm	Upper Arm
Wrist Flexion/Extension	X_W	Palm	Forearm
Wrist Abduction/Adduction	Y_W	Palm	Forearm
Wrist Pronation/Supination	Z_W	Palm	Forearm
Torso Flexion/Extension	X_H	Torso	Hip
Torso Right Lean/Left Lean	Y_H	Torso	Hip
Torso Right Rotation/Left Rotation	Z_H	Torso	Hip
Hip Flexion/Extension	X_T	Hip	Torso
Hip Abduction/Adduction	Y_T	Hip	Torso
Hip Internal Rotation/External Rotation	Z_T	Hip	Torso
Knee Flexion/Extension	X_K	Shank	Hip
Ankle Flexion/Extension	X_A	Foot	Shank

2.3 Data Analysis

Following the completion of testing, raw Vicon data was processed first in Vicon IQ to reconstruct and label the trajectories. The 3-D marker data was then loaded into Vicon BodyBuilder to calculate joint angles with a custom written BodyBuilder model. Joint angle data was then consolidated into a single spreadsheet, per subject, to enable calculation of intra-subject maximum ROM for every joint across all the functional tasks. Each maximum joint angle for every subject was compared to the visual representation of the data in Vicon BodyBuilder to visually verify the calculated ROM as previously discussed. Figure 7 illustrates this process by showing the marker set overlaid on a model subject and the interface from Vicon BodyBuilder plotting shoulder flexion. The sample subject is inserted here for clarity and would not be present during the actual process of visually verifying the maximum joint angles. The subject-specific maximum functional ROMs were compiled into a single spreadsheet containing the ROM data for all 24 subjects of functional data and 17 subjects of isolated maximum data. Single values were extracted for creation of design requirements based on the statistical mode of the functional ROM data.

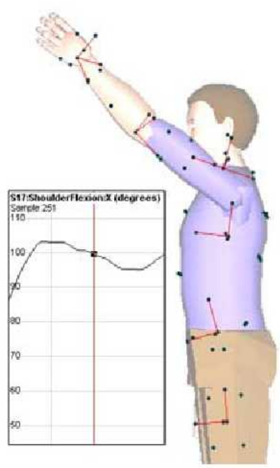


Figure 7: Bodybuilder Interface Superimposed on Model Subject

Analysis of suited data was completed in a manner analogous to unsuited with subtle differences to accommodate the increased complexity of the data.

After functional mobility data had been gathered for all twenty unsuited subjects, the mode of the range of motion values was calculated for each joint motion. The mode was used due to it being less vulnerable to outliers than the median or the mean. The mode is uniquely qualified as a statistical method for quantifying data when different approaches are taken in the completion of a functional task. If, for example, slightly more than half of the subject pool used a large amplitude of some specific joint rotation to complete a task and the remaining subjects completed the task a different way that used a very small rotation of the same joint, the mean would report a value in the middle, denying more than half the subjects the required joint mobility to complete the task in their preferred manner. The median would likely report one of the lowest values in the larger group, still not providing many of the subjects with the mobility they utilized to complete the task in their desired fashion. The mode would have the best chance of falling in the highest density of data points and capturing all the required mobility for most subjects to perform the task.

Because Bodybuilder provides angles calculated to six decimal places, the reported joint angles were rounded to the nearest multiple of 5 degrees. Inspection of the data suggested that consecutive extreme ranges of motion for a variety of cyclic tasks were separated by no more than 5 degrees. In other words, as a subject completed a cyclic task (i.e., hammering, walking or shoveling), they appeared to reach a consistent peak range of motion throughout the test, which generally varied less than 5 degrees. The rounding increased the chance of a unique mode being calculated for the data. For example, the set of values 125.4, 150.3, 148.9, and 138.0 has no unique mode. When they are rounded to 125, 150,150 and 140, then 150 is the mode of the data.

Since the mode is defined as the most frequently occurring value, it is possible for multiple modes to exist for a given measure. This problem would prevent a single value from being reported as a design requirement. When multiple modes existed, the mode that was closest to the mean was selected.

The mode was not used to report suited functional mobility, since only four subjects tested in each suit, reducing the likelihood of a unique mode without excessive rounding. Instead, the mean was used to capture the average suited mobility across subjects.

3. RESULTS

3.1 Results for Individual Joints

In an effort to better organize the large amount of data collected in this study, the analysis has been broken down into sections by joint. For instance, the ankle mobility section will compare the recorded range of motion for the human ankle to the mobility of the ankle joint when a subject is wearing each of the tested suits: the ACES, I-Suit, MK-III and EM-ACES. The ACES, EM-ACES and I-Suit are considered in both the pressurized and unpressurized states, while the MK-III, due to its weight, is only worn pressurized for this 1-G study. Range of motion data is supplemented by photographs of suited neutral posture, discussion of subject experience and fit and their impact on mobility, and identification of outliers, such as subjects whose motivation and/or experience seemed to provide an advantage. All values reported in the following tables represent averages across all subjects who completed the specified condition, with the exception of the unsuited functional data which represents the mode of the 20 subjects.

Subjects and Their Suited Conditions:

Not all of the subjects were tested in all of the suits, and one subject completed only functional trials in the unpressurized I-suit. Table 2 denotes the conditions completed by each subject. The letter A indicates the functional trials, while the letter B represents the isolated trials. Only subject 3 completed both functional and isolated testing in all four suits.

Table 2: Subjects and their Suited Conditions (A for Functional, B for Isolated)

	Suited Condition							
Subject	Unsuited	Unpress I-Suit	Press I-Suit	Unpress ACES	Press ACES	Press MK III	Unpress EM-ACES	Press EM-ACES
1	A,B	A,B	A,B	None	None	A,B	None	None
2	A	A	A,B	A,B	A,B	A,B	None	None
3	A,B	A,B	A,B	A,B	A,B	A,B	A,B	A,B
4	A,B	A,B	A,B	A,B	A,B	None	A,B	A,B
5	A,B	None	None	A,B	A,B	None	None	None
6	A,B	None	None	None	None	A,B	A,B	A,B
7	A,B	None	None	None	None	None	A,B	A,B

Key to understanding bar charts

The bar charts in the results section display range of motion data in a format that allows comparison between suits. Take the ankle for example: there will be a total of four charts to describe this single-axis joint. Each direction of motion (dorsiflexion and plantar flexion) will be treated separately. These will each be further broken down into a chart of unpressurized suited data and a chart of pressurized suited data. The four charts will be as follows:

- Ankle Dorsiflexion, Unpressurized
- Ankle Plantar Flexion, Unpressurized
- Ankle Dorsiflexion, Pressurized
- Ankle Plantar Flexion, Pressurized

Each chart also includes the subjects' unsuited data for comparison. This is provided on the far left side of the chart.

Each suit, and the unsuited data, has a further division: functional or isolated. These two sections are separated by a dotted line. This allows easy comparison of the mobility a subject was capable of achieving unassisted, to what range of motion they used during the functional trials.

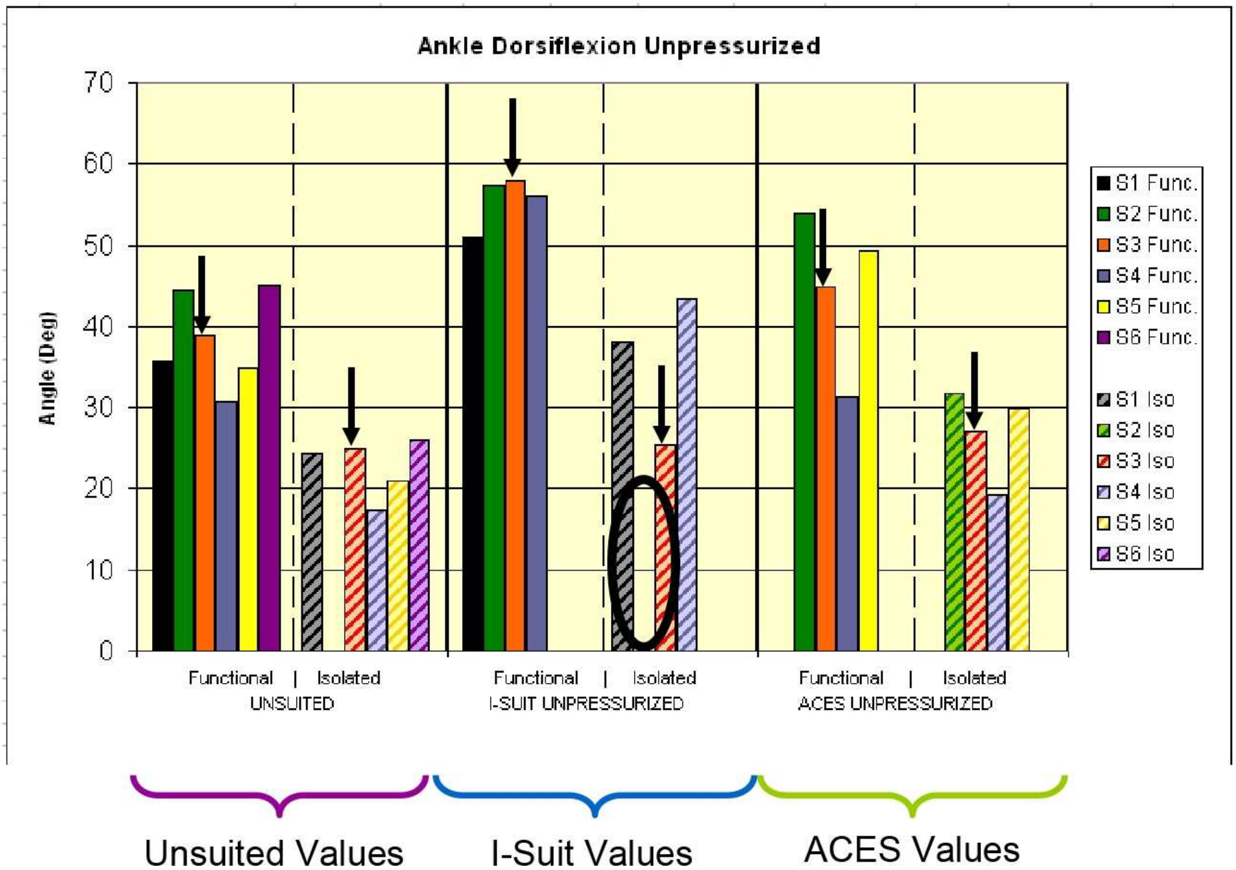


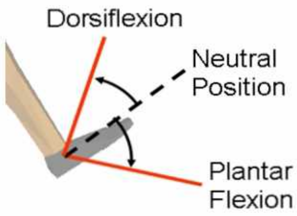
Figure 8: Bar Chart Key

The arrows in Figure 8 indicate data points for one subject across all the conditions.

The circled area points out a gap, which indicates that a subject did not have data for this condition. In this specific case, the gap occurs because subject 2 did not complete an isolated trial in the unpressurized I-suit. Other gaps occur because, for example, subjects 1 and 6 did not test at all in the ACES.

The curly braces (added here for emphasis) denote the different suited conditions displayed in this chart: unsuited, I-suit and ACES. Because this is the unpressurized case, there is no data for the MK-III.

Table 3: Ankle Mobility



Ankle	Observed Range of Motion					
	Isolated			Functional		
	Dorsi	Plantar	Range	Dorsi	Plantar	Range
Unsuited All Subjects	22	-51	73	35	-40	75
ACES Unpress	27	-34	62	45	-30	75
ACES Press	36	-7	43	47	-5	52
MK III Press	35	-31	66	50	-38	88
I-Suit Unpress	36	-30	67	56	-34	90
I-Suit Press	42	-11	53	55	-14	69
EM-ACES Unpress	27	-30	57	49	-26	75
EM-ACES Press	26	-10	36	54	-18	72

*All Units in Degrees

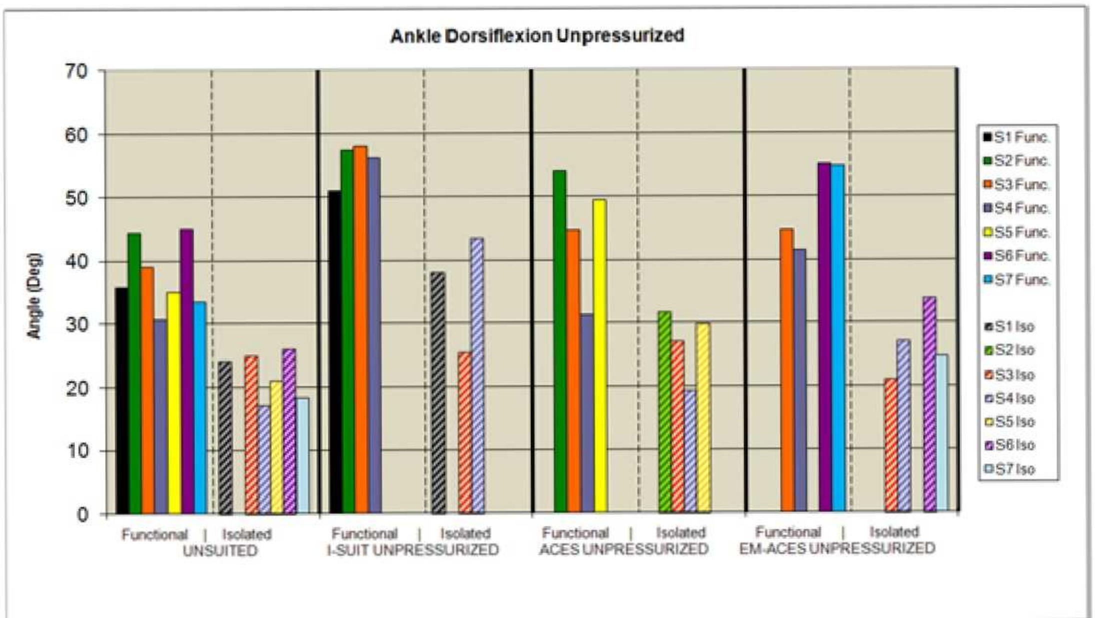


Figure 9: Ankle Dorsiflexion by Unpressurized Suit, Compared across Subjects

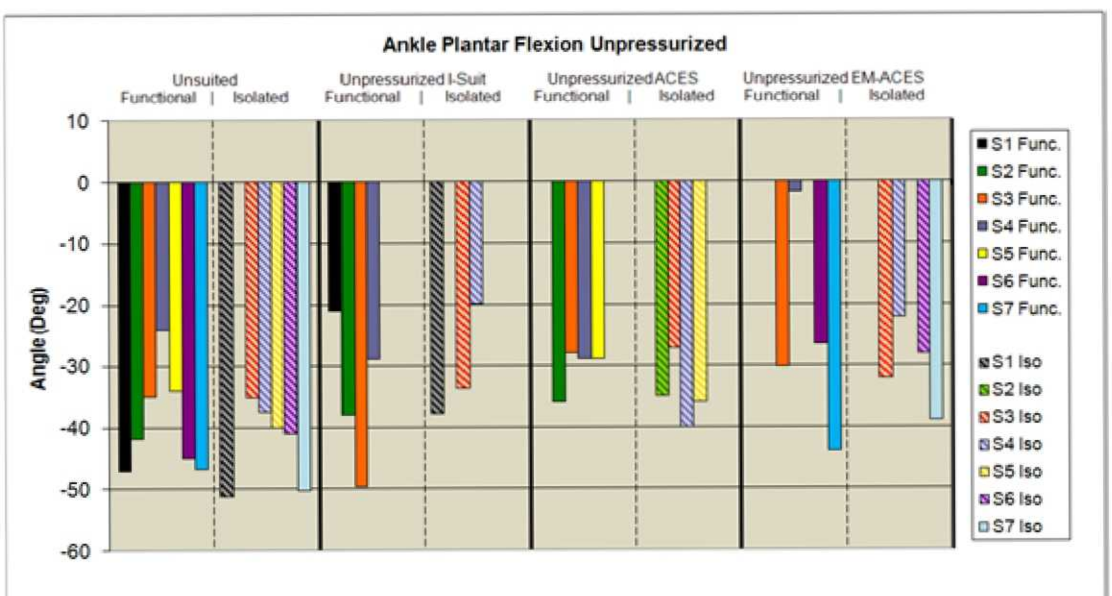


Figure 10: Ankle Plantar Flexion by Unpressurized Suit, Compared across Subjects

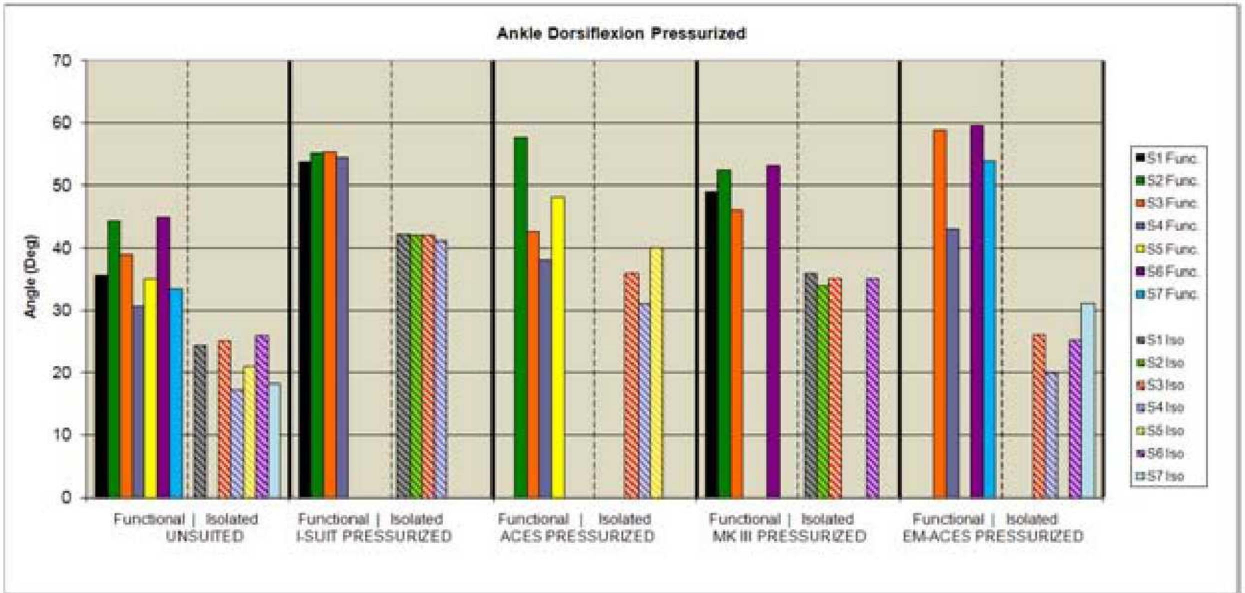


Figure 11: Ankle Dorsiflexion by Pressurized Suit, Compared across Subjects

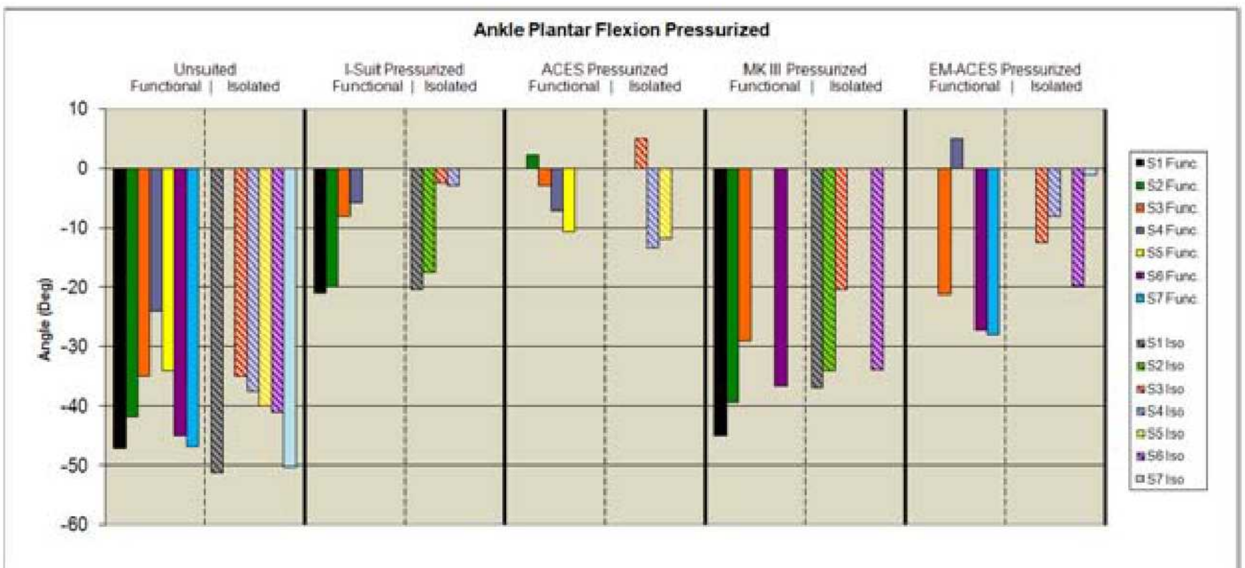


Figure 12: Ankle Plantar Flexion by Pressurized Suit, Compared across Subjects

The Ankle

In general, the suit boots tended to restrict a subject's ability to plantar flex their ankle – which is intuitive, considering the restrictions normally associated with a boot. When suited the subjects tended to have higher values for dorsiflexion, especially during actions such as climbing a ramp in a heavy suit.

<u>Unsuited Ankle Dorsiflexion and Plantar Flexion</u>

- Unsuited ankle mobility was unrestrained by footwear present in suited conditions, resulting in the highest observed plantar flexion of any condition. Isolated dorsiflexion was performed with no external load driving the motion, whereas the functional case benefited from additional load driving dorsiflexion.

ACES Ankle Dorsiflexion and Plantar Flexion

- Even in the unpressurized case, ACES ankle range of motion is lower than in the unsuited testing, which was conducted wearing socks. The largest mobility decrease is in plantar flexion, and is likely due to the restrictions of a boot (Figure 13).

Figure 13: Ankle Mobility, Suited vs. Unsuited

- Pressurized, the ACES ankle has a bias towards dorsiflexion that is reportedly uncomfortable (Figure 14).

Figure 14: ACES Pressurized Ankle Bias

MK III Ankle Dorsiflexion and Plantar Flexion

- The MK-III's ankle dorsiflexion and plantar flexion were approximately symmetrical, suggesting less of the dorsiflexion bias seen in the I-suit and ACES.

I-Suit Ankle Dorsiflexion and Plantar Flexion

- The unpressurized I-suit ankle has a slightly higher range than unsuited in the functional case, which involves motions like recovery from prone, crawling, and walking up and down ramps and ladders in the heavy suit.
- The pressurized I-suit ankle often saw high values of dorsiflexion, especially during functional trials (see Figure 15) where a lot of weight was placed on the joint. Ankle dorsiflexion values also tend to increase as the knees are bent, if the feet remain firmly planted on the ground.

EM-ACES Ankle Dorsiflexion and Plantar Flexion

- Although the ACES and the EM-ACES had similar isolated ankle mobility, the pressurized EM-ACES used more ankle mobility while performing the functional tasks. This is expected because the pressurized EM-ACES could perform more of the ambulatory tasks than the pressurized ACES, including motions such as crawling and kneeling that tended to maximize ankle plantar flexion and dorsiflexion, respectively.

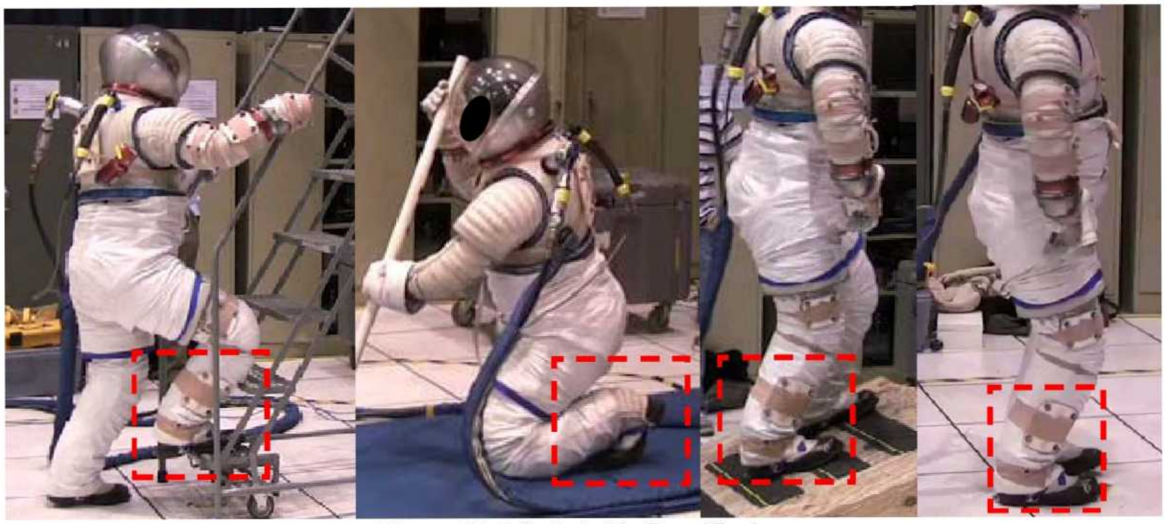
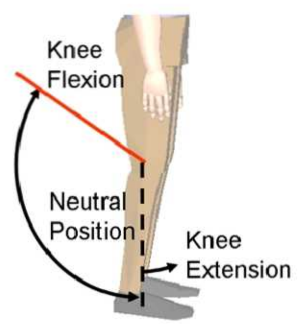


Figure 15: I-Suit Ankle Dorsiflexion

Table 4: Knee Mobility



Knee

Observed Range of Motion						
	Isolated			Functional		
	Flex	Ex	Range	Flex	Ex	Range
Unsuited All Subjects	-127	0	127	-140	0	140
ACES Unpress	-111	0	111	-126	5	131
ACES Press	-123	-29	94	-95	-41	54
MK III Press	-105	-8	97	-129	-6	123
I-Suit Unpress	-91	-14	77	-112	-7	105
I-Suit Press	-109	-16	93	-123	-12	111
EM-ACES Unpress	-148	-8	140	-151	-1	151
EM-ACES Press	-123	1	124	-143	14	157

*All Units in Degrees

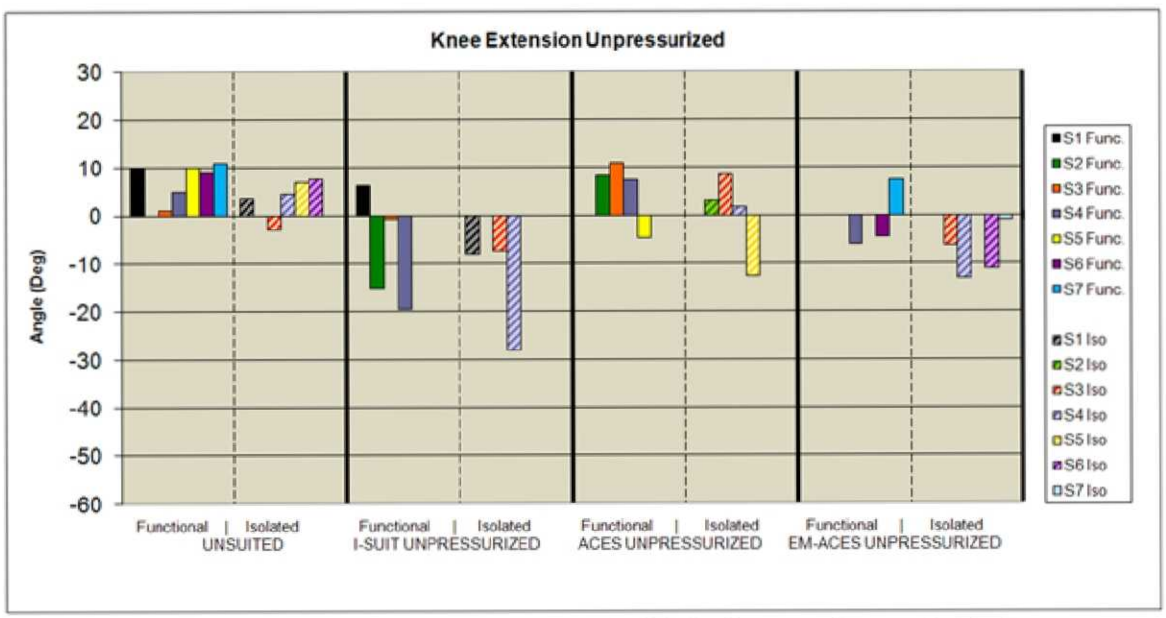


Figure 16: Knee Extension by Unpressurized Suit, Compared across Subjects

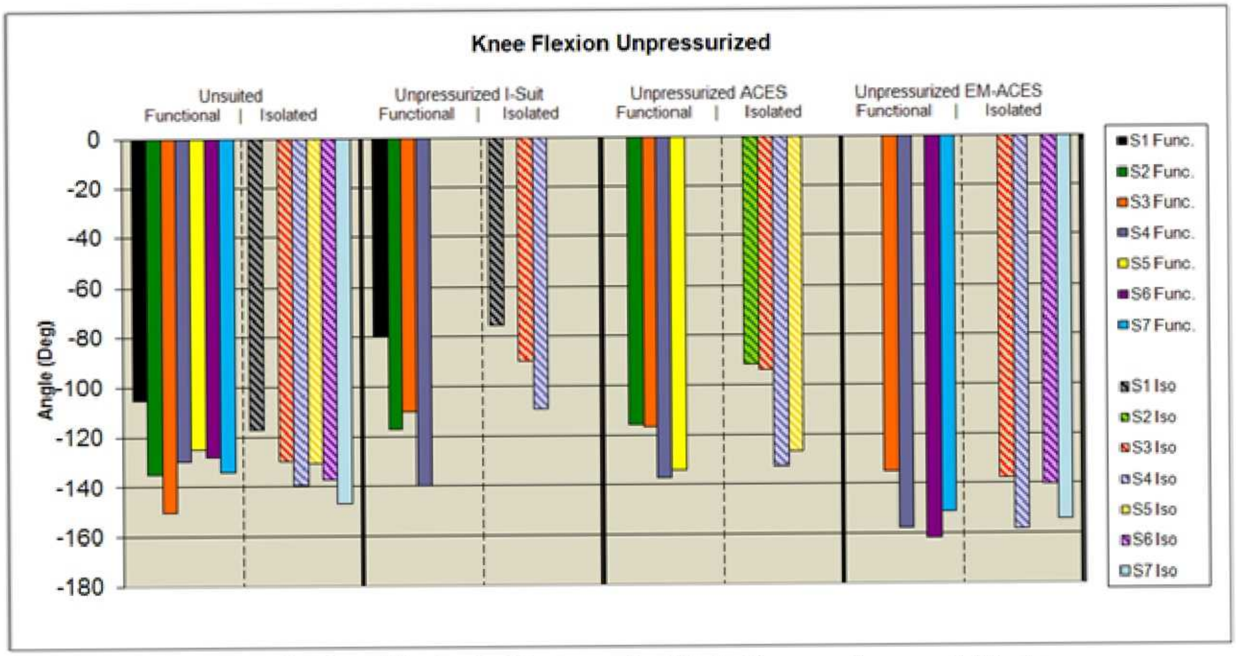


Figure 17: Knee Flexion by Unpressurized Suit, Compared across Subjects

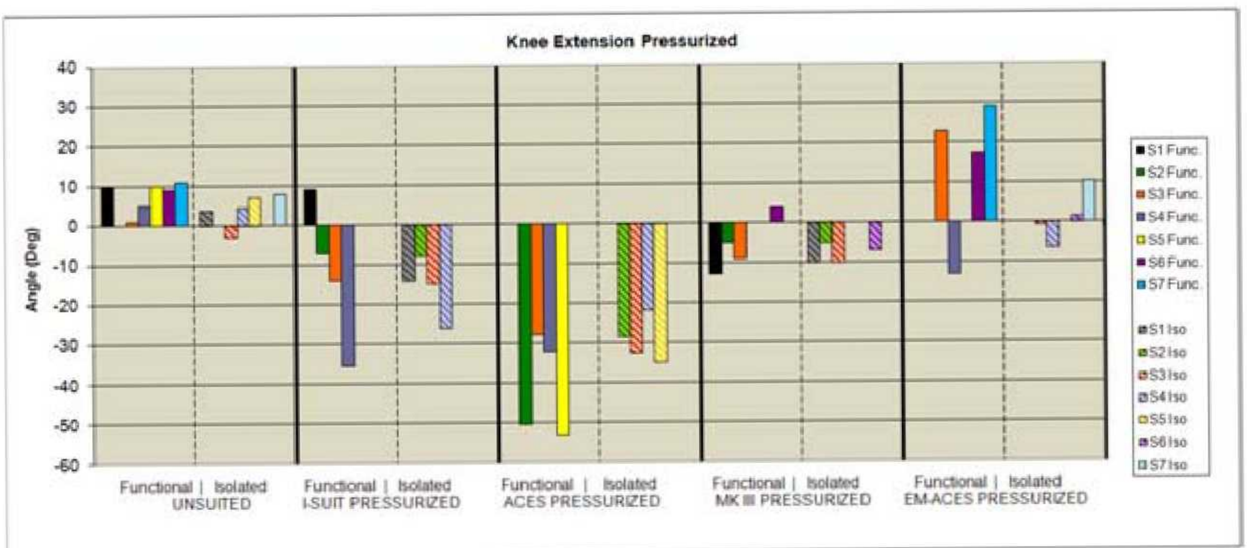


Figure 18: Knee Extension by Pressurized Suit, Compared across Subjects

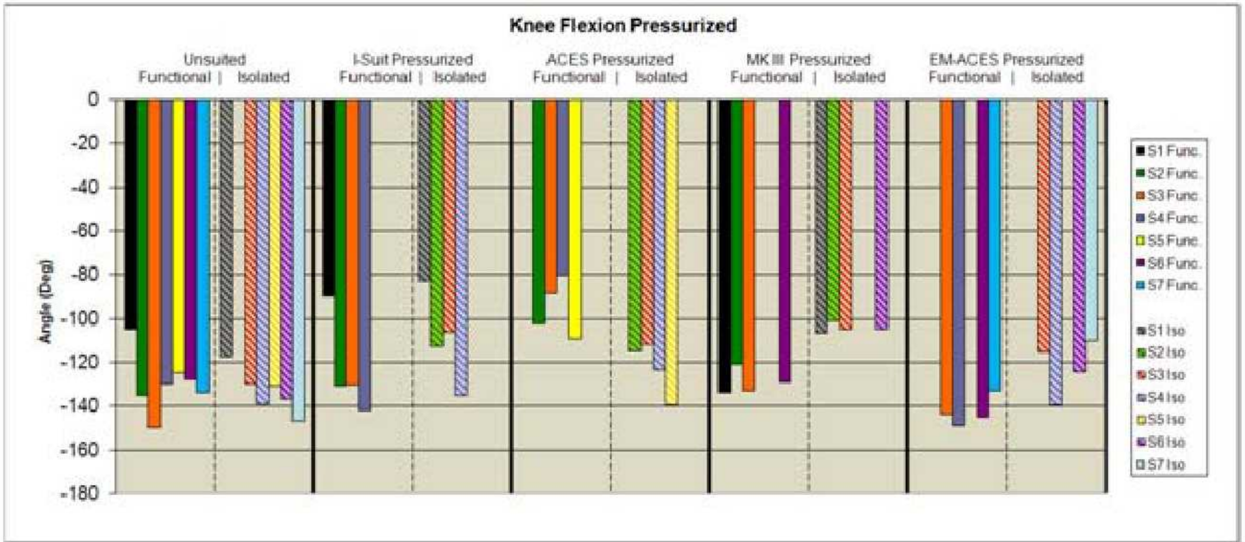


Figure 19: Knee Flexion by Pressurized Suit, Compared across Subjects

The Knee

The knee joint is comparable to the ankle in that it often possesses higher flexion in functional situations where a force beyond just subject musculature is driving the movement. The suits seem to induce a bias in favor of increased knee flexion, possibly stemming from suit architecture or suboptimal suit fit.

Unsuited Knee Flexion

- Unsuited knee flexion was observed to be higher in functional instances possibly due to compound joint motion and more favorable loading conditions such as when the lower leg isn't moving against gravity.

ACES Knee Flexion

- The pressurized ACES knee appeared to be biased in flexion, as seen in Figure 20.

Figure 20: Pressurized ACES Knee Bias

MK III Knee Flexion

- The MK III suit appeared to have a slightly lower bias towards flexed knees than the pressurized I-suit (see Figure 21). This could have been due to shorter soft goods legs in the MK III, compared to the I-suit.

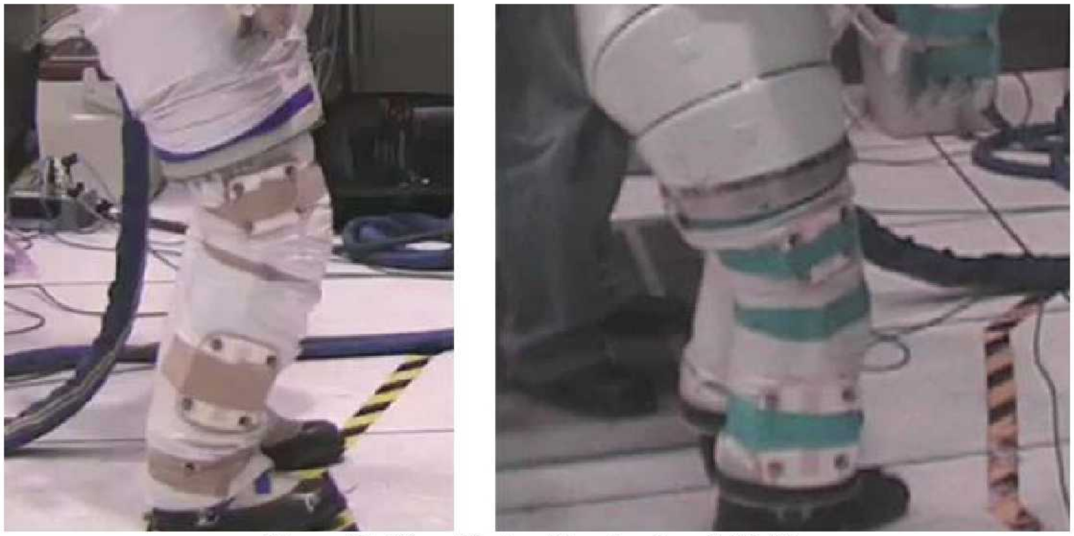


Figure 21: Knee Flexion Bias, I-suit vs. MK-III

<u>I-suit Knee Flexion</u>

- When pressurized the I-suit knee seems to have a slight bias towards flexion. This average value, however, may be exaggerated by the stance of one particular subject, who was the tallest and operated with knees that were very obviously bent (see Figure 22 a,b). The legs of another subject are seen from the side in Figure 22c.

Figure 22: Pressurized I-suit Knee Flexion: a) Tall Subject Walking b) Tall Subject Standing c) Shorter Subject Standing

- During extreme instances of isolated knee flexion in the unpressurized I-suit, markers tended to be occluded by additional fabric bulk, potentially decreasing the reported range

<u>EM-ACES Knee Flexion</u>

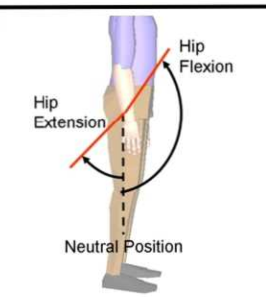
- The knee of the EM-ACES appeared to have substantially improved mobility over the ACES, although this may have partially been amplified by the more upright stance of the EM-ACES enabling more functional tasks to be attempted.
- The EM-ACES could stand upright fairly easily, but with no significant hip joint, any attempt to pick items off the ground resulted in extremely high values of knee flexion.
- For instance, while picking up a box from the ground, subjects had to severely flex their knees to get low enough to reach the object – an action that appeared to require the application of body weight to flex the joint.

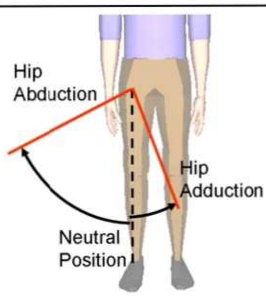
Figure 23: Unsuited Kneeling (Left) versus Kneeling in the Pressurized EM-ACES

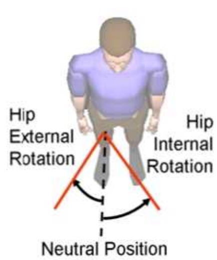
- For all subjects, knee flexion was maximized in the pressurized EM-ACES during kneeling. In fact, this flexion was higher on average than unsuited knee flexion. For example, see Figure 23 above, where unsuited kneeling is compared to kneeling in the pressurized EM-ACES.

Table 5: Hip Mobility

Figure







Hip — Observed Range of Motion

	Isolated			Functional		
	Flex	Ex	Range	Flex	Ex	Range
Unsuited All Subjects	145	-45	190	165	-15	180
ACES Unpress	97	-28	125	136	-27	163
ACES Press	56	34	22	79	37	42
MK III Press	73	-21	94	127	-16	143
I-Suit Unpress	110	-15	125	150	-15	165
I-Suit Press	81	-21	102	167	-31	198
EM-ACES Unpress	112	-9	122	140	-11	151
EM-ACES Press	38	13	25	56	10	47

	Isolated			Functional		
	Ab	Ad	Range	Ab	Ad	Range
Unsuited All Subjects	-63	21	84	-25	15	40
ACES Unpress	-45	27	72	-29	21	50
ACES Press	-18	-3	15	-19	-6	13
MK III Press	-14	35	49	-32	24	56
I-Suit Unpress	-29	25	54	-45	15	60
I-Suit Press	-23	32	55	-41	27	68
EM-ACES Unpress	-39	19	58	-38	20	58
EM-ACES Press	-4	13	17	-5	10	15

	Isolated			Functional		
	Int Rot	Ext Rot	Range	Int Rot	Ext Rot	Range
Unsuited All Subjects	37	-31	68	50	-45	95
ACES Unpress	15	-26	41	36	-37	73
ACES Press	13	5	8	12	0	12
MK III Press	33	-49	82	45	-63	108
I-Suit Unpress	48	-34	82	46	-21	67
I-Suit Press	36	-51	87	40	-39	79
EM-ACES Unpress	19	-26	46	29	-32	61
EM-ACES Press	-1	-10	9	5	-9	14

*All Units in Degrees

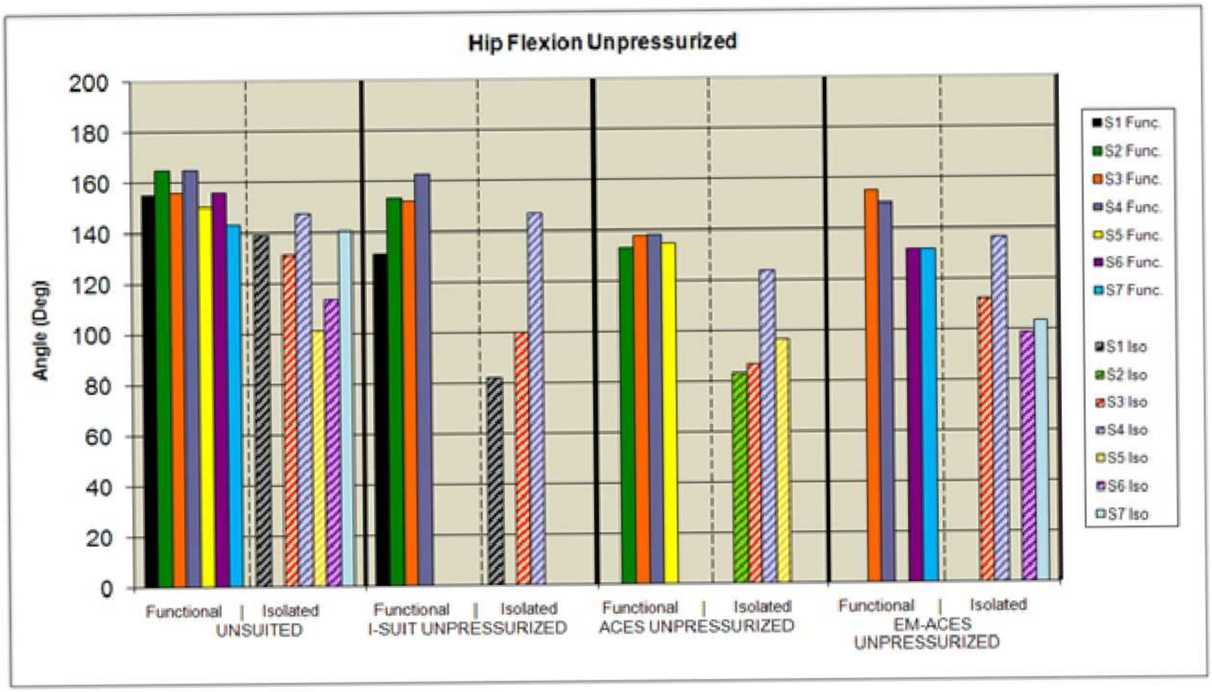


Figure 24: Hip Flexion by Unpressurized Suit, Compared across Subjects

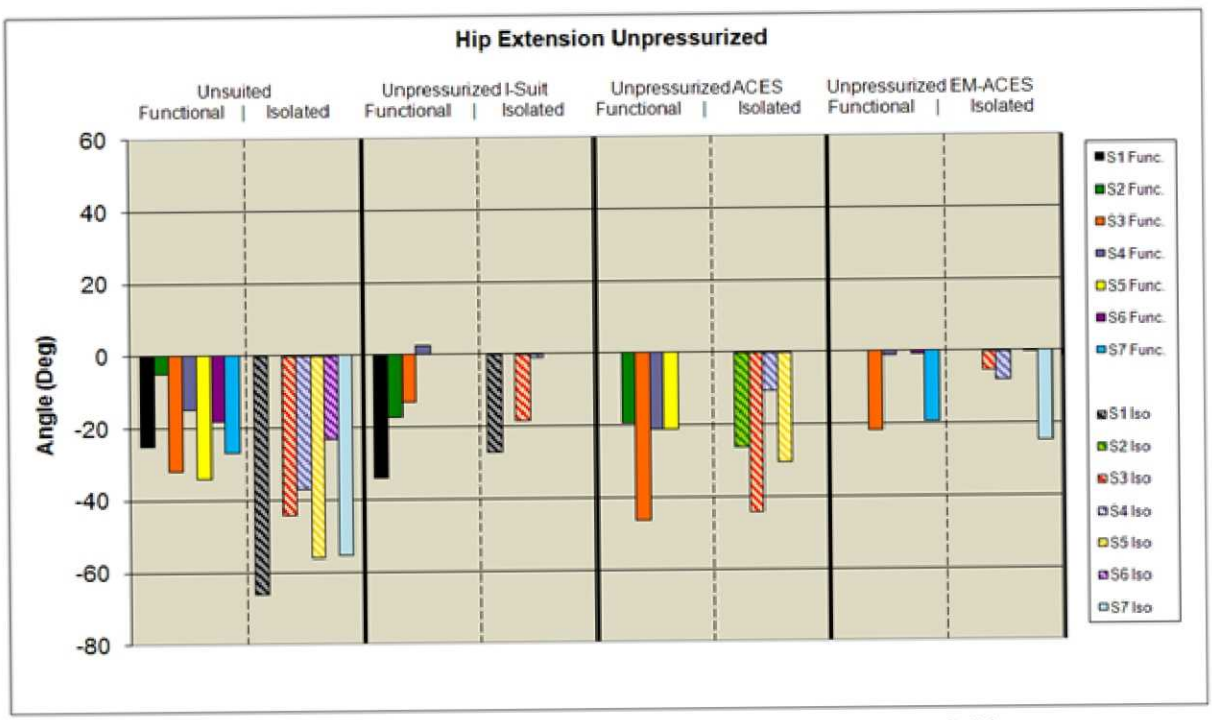


Figure 25: Hip Extension by Unpressurized Suit, Compared across Subjects

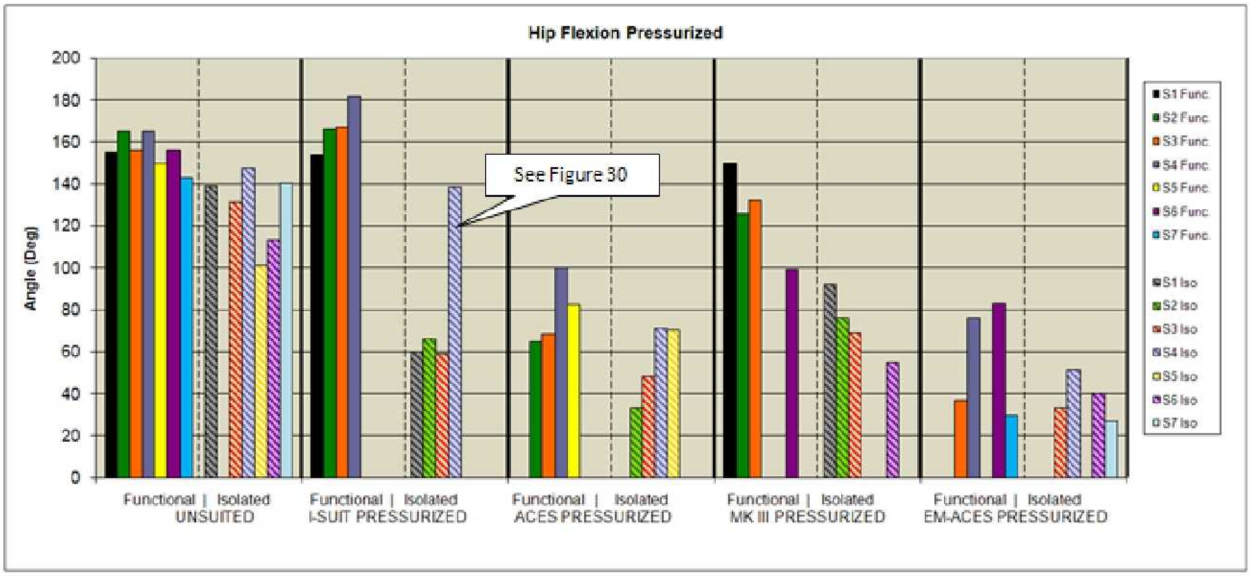


Figure 26: Hip Flexion by Pressurized Suit, Compared across Subjects

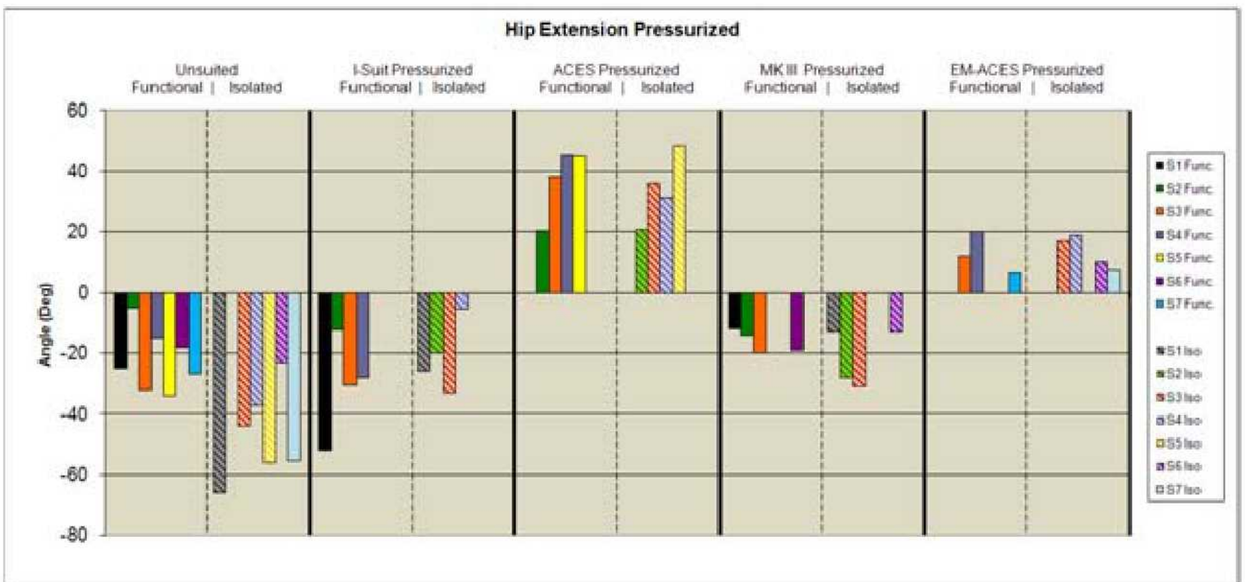


Figure 27: Hip Extension by Pressurized Suit, Compared across Subjects

The Hip

The human hip joint is a complex, multi-axis joint whose motion is approximated by elaborate systems of bearings and fabric joints in the suits. These different systems have varying capacities for matching unsuited mobility sometimes leading to altered movement strategies. In addition, the weight and bulk of these components can themselves restrict mobility.

<u>Unsuited Hip Flexion</u>

- Isolated hip flexion was likely lower than functional flexion due to resistance of gravity in the isolated position and compound joint movements in functional tasks. The isolated position involved standing and flexing the hip whereas functional tasks routinely included seated, crawling, or kneeling positions that brought the hip closer to the torso.

ACES Hip Flexion

- When the ACES was pressurized, the subject's ability to lean back/extend their hips may have been restricted by the cinching strap on their chest
- For safety reasons, ingressing the recumbent seat in the ACES involved depressurizing the suit, allowing the subject to arrange him or herself on the seat, and then repressurizing in the new configuration.

MK III Hip Flexion

- The two most experienced subjects had the highest value of torso flexion in both the functional and isolated cases. To obtain their maximum hip/torso flexion, they splayed their legs and then rotated about their hip bearings (see Figure 28). As in the I-suit, they actually sat forward off of the chair to obtain their maximum flexion.

Figure 28: MK III Seated Torso Flexion, Experienced Subjects

- One subject, who the suit techs said had too long of a suit torso, and who was also one of the least experienced subjects, had the lowest torso/hip flexion. When sitting, this subject did not splay their legs, and therefore did not take advantage of the hip bearings to rotate forward – instead hitting a hard stop when they reached the limit of the waist joint (Figure 29).

Figure 29: MK III Seated Torso Flexion, Less Experienced Subject

I-Suit Hip Flexion

- Isolated hip flexion values for the I-suit, both pressurized and unpressurized, are skewed upwards by the performance of one subject, shown on the right in Figure 30. This subject achieved approximately 1.5 times the other subjects' average in the unpressurized case, and twice their average mobility in the pressurized case.

Figure 30: I-Suit Hip Flexion: Average (Left) and Above Average (Right)

- Subjects could achieve high values of hip/torso flexion in the pressurized I-suit in a seated posture, by sitting forward off of the chair and reaching down between their legs (Figure 31). The subject on the right is an extreme case. It should also be noted that this subject had unintentionally popped open a waist sizing element on the I-suit, increasing his effective torso length and perhaps contributing to his flexibility.

Figure 31: Pressurized I-suit Max Hip Flexion

- The high value of pressurized hip extension is related to a kneeling posture taken by two subjects in the I-suit, who had one knee behind the centerline of their torso and used a mobility aid to help themselves to their feet.

EM-ACES Hip Flexion

- When pressurized the EM-ACES has a more vertical stance than the pressurized ACES, which has a neutral posture featuring noticeably flexed hips. The more upright stance enables the EM-

ACES to stand and walk, but not to sit, while the opposite is true for the ACES. The suits have the same hip/torso flexion/extension ranges.

- The pressurized EM-ACES maximized hip flexion while kneeling (see Figure 23) and while picking up a box from the floor (see Figure 32).

Figure 32: Box Pickup in the Pressurized EM-ACES

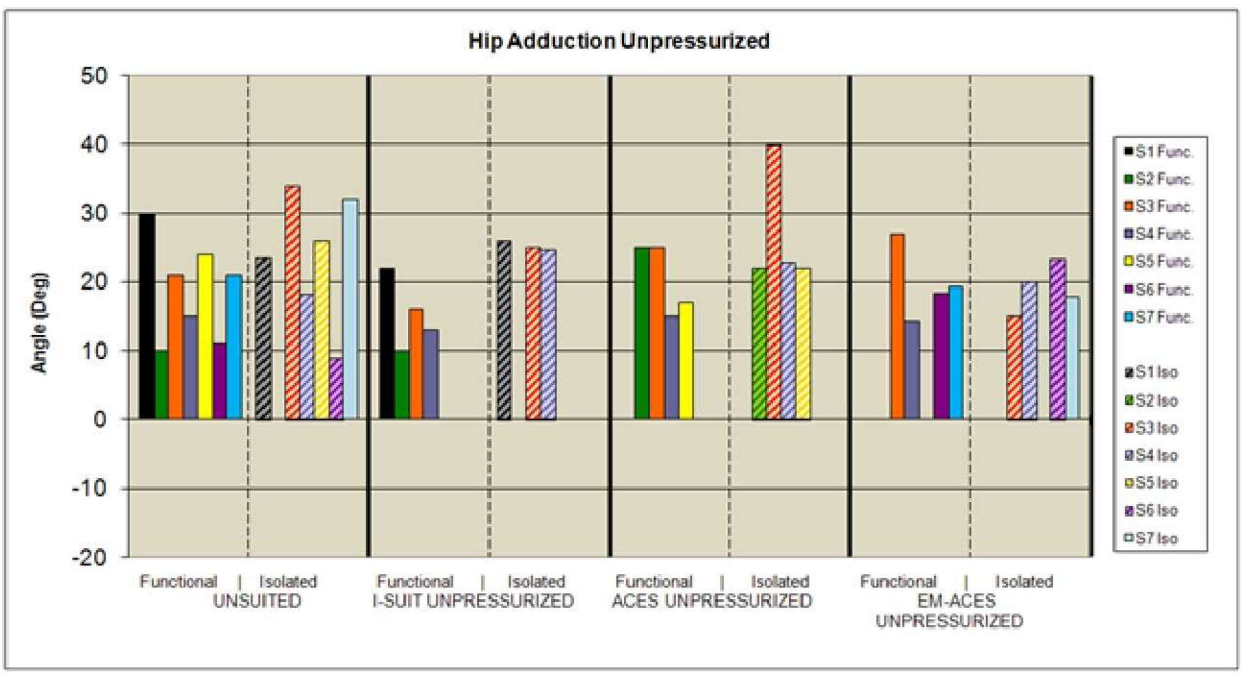


Figure 33: Hip Adduction by Unpressurized Suit, Compared across Subjects

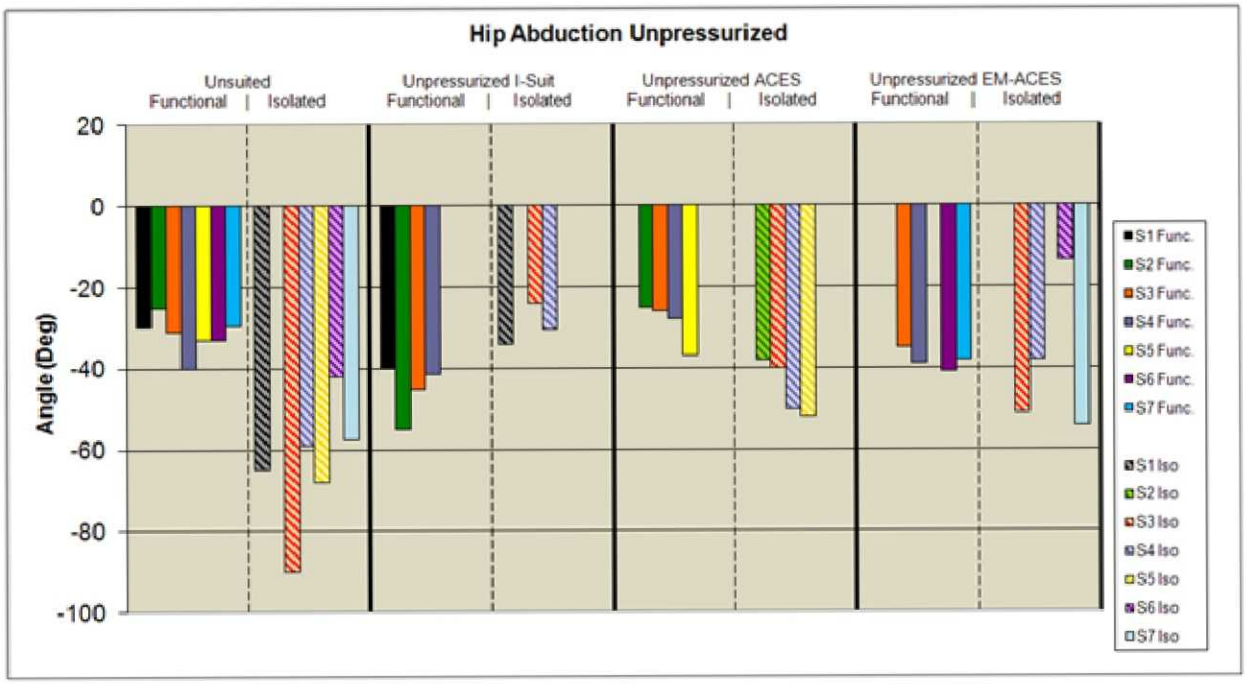


Figure 34: Hip Abduction by Unpressurized Suit, Compared across Subjects

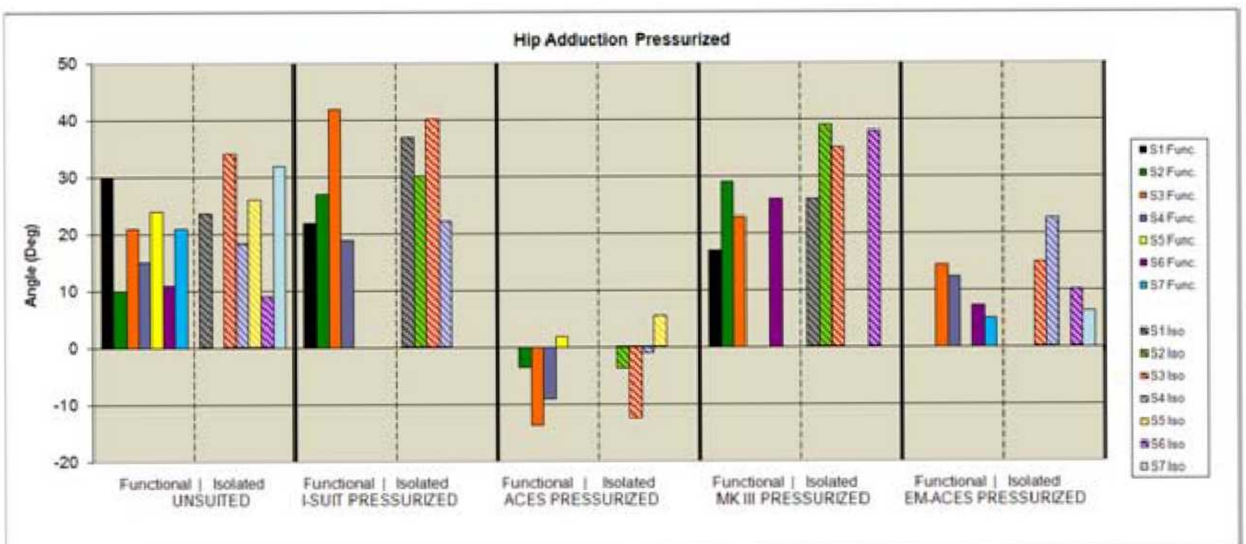


Figure 35: Hip Adduction by Pressurized Suit, Compared across Subjects

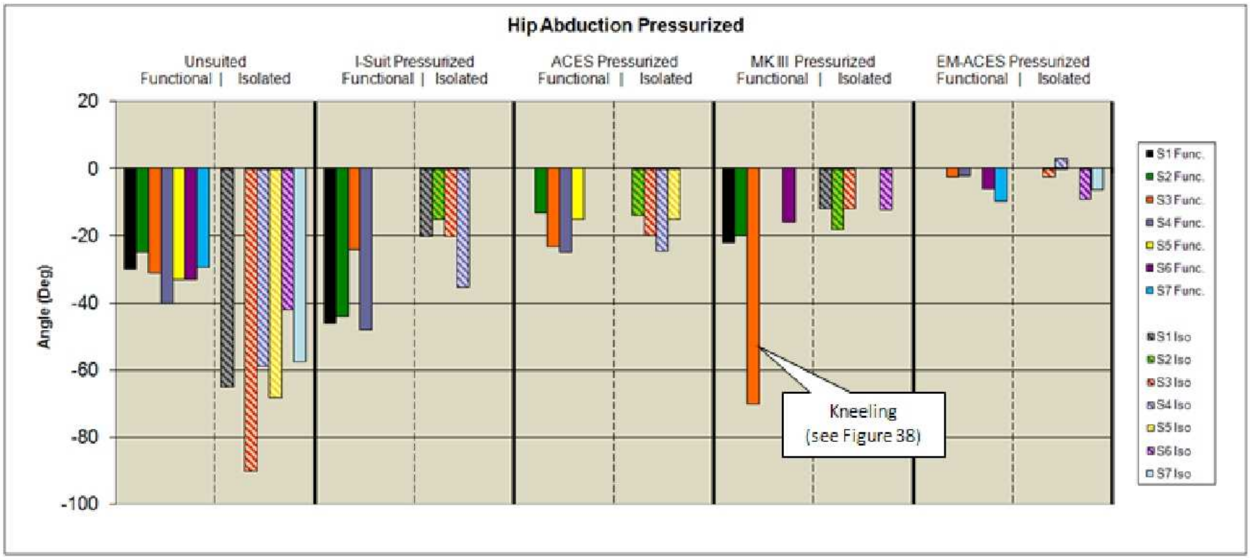


Figure 36: Hip Abduction by Pressurized Suit, Compared across Subjects

<u>Unsuited Hip Abduction/Adduction</u>

- Unsuited hip abduction/adduction capacity exceeded functionally necessary mobility. Motion in this plane, adduction especially, is a secondary component of hip mobility behind flexion/extension.

<u>ACES Hip Abduction/Adduction</u>

- In the pressurized case, abduction/adduction was minimal. The static abduction value is likely a result of the suit's neutral splayed-leg stance.

<u>MK III Hip Abduction/Adduction</u>

- Isolated hip abduction was very low, since it involved lifting the suit leg out to one side, likely leading to hardware-to-hardware contact (Figure 37). Adduction was higher because the bearings allowed the subject to swing their leg across their body – although the programming in the suit led to some flexion during this motion.

Figure 37: MK-III Isolated Hip Abduction

- In the functional case, the suit achieved much larger adduction and abduction values. For each subject, the kneeling trial led to the highest hip abduction. One subject in particular had extremely high hip abduction values while leaning sideways to touch the ground, during their kneeling trial (see Figure 38).

Figure 38: Functional Hip Abduction in the MK-III

I-Suit Hip Abduction/Adduction

- The high values of functional hip abduction seen in the I-suit are a result of a posture taken while egressing the recumbent seat: with the legs splayed out on either side of the seat back. The average value is even slightly low, skewed down by the fact that one subject chose a different method of egressing the seat, swinging their leg across the body (Figure 39, Right).

Figure 39: Recumbent Seat Egress Trial in the I-Suit

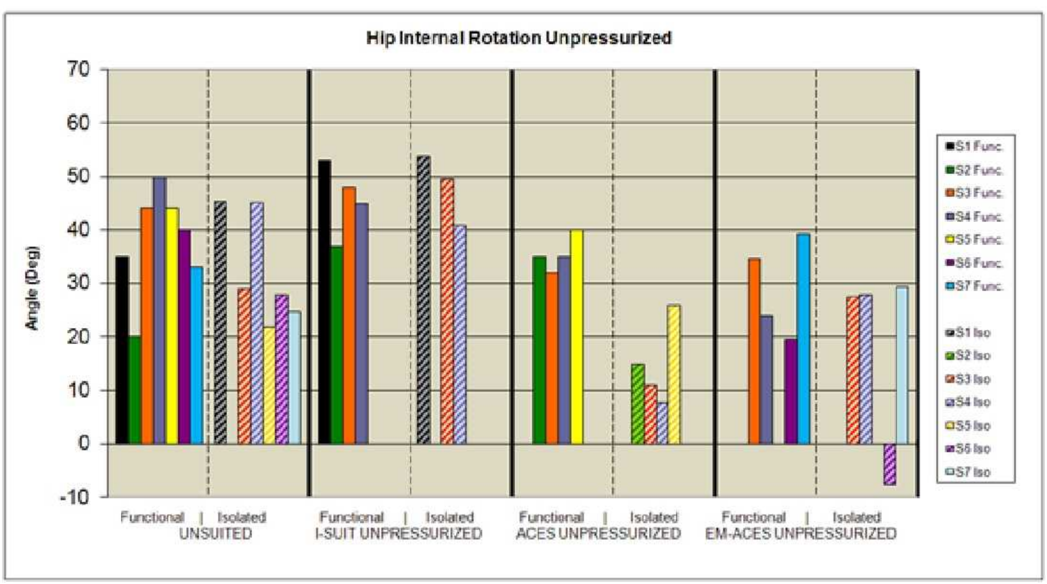


Figure 40: Hip Internal Rotation by Unpressurized Suit, Compared across Subjects

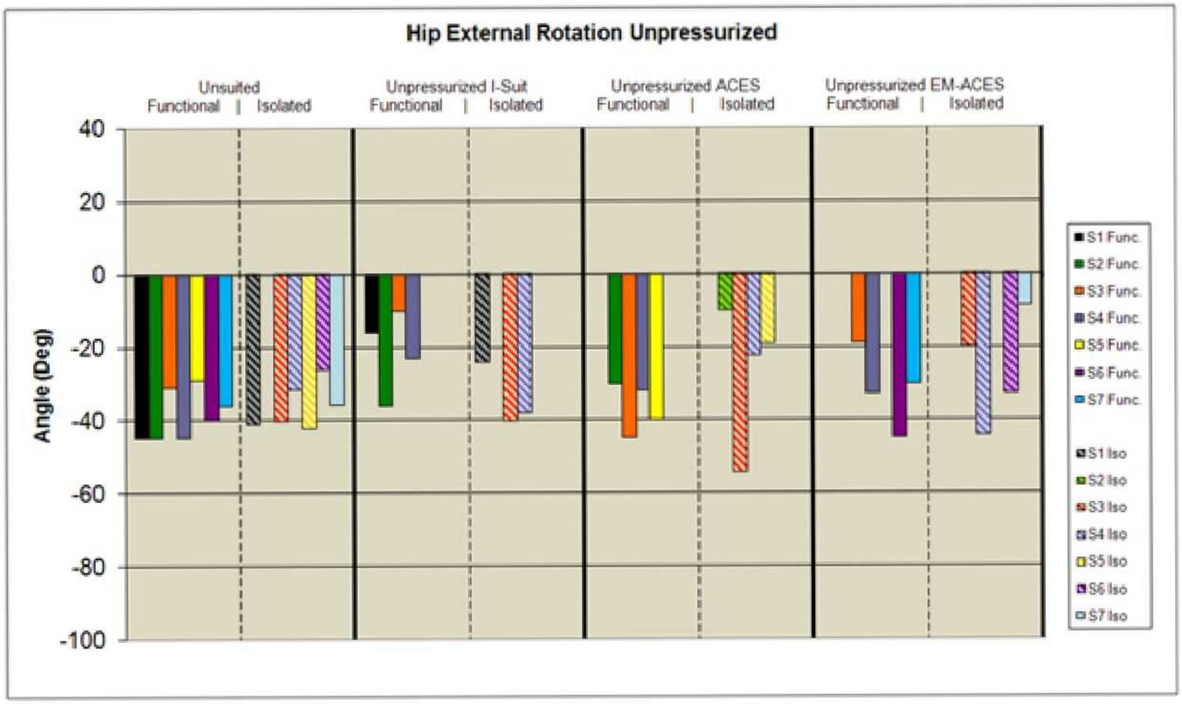


Figure 41: Hip External Rotation by Unpressurized Suit, Compared across Subjects

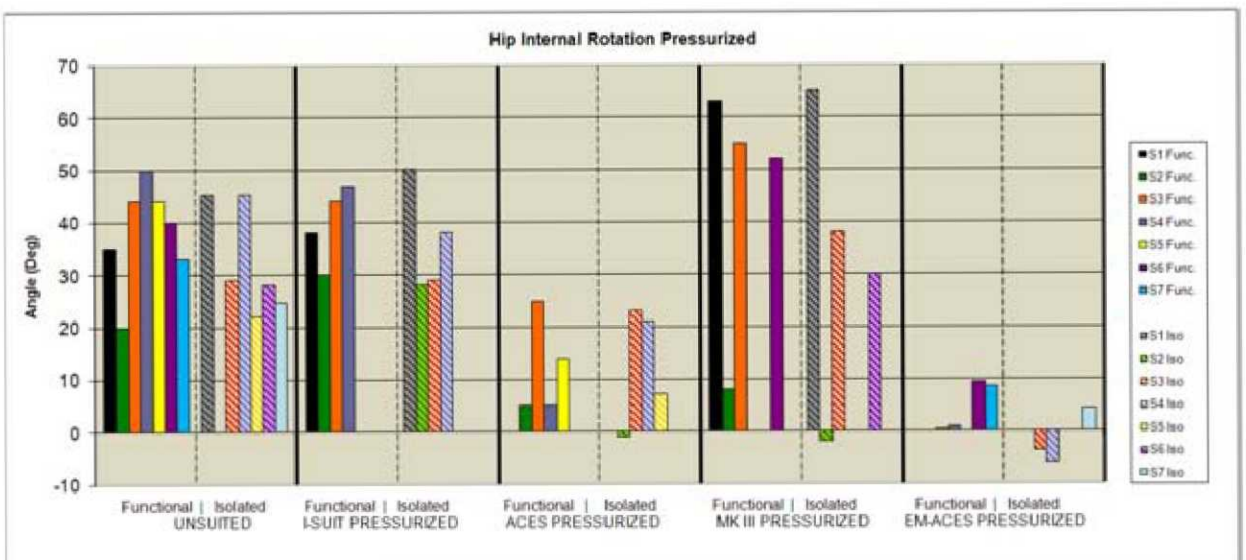


Figure 42: Hip Internal Rotation by Pressurized Suit, Compared across Subjects

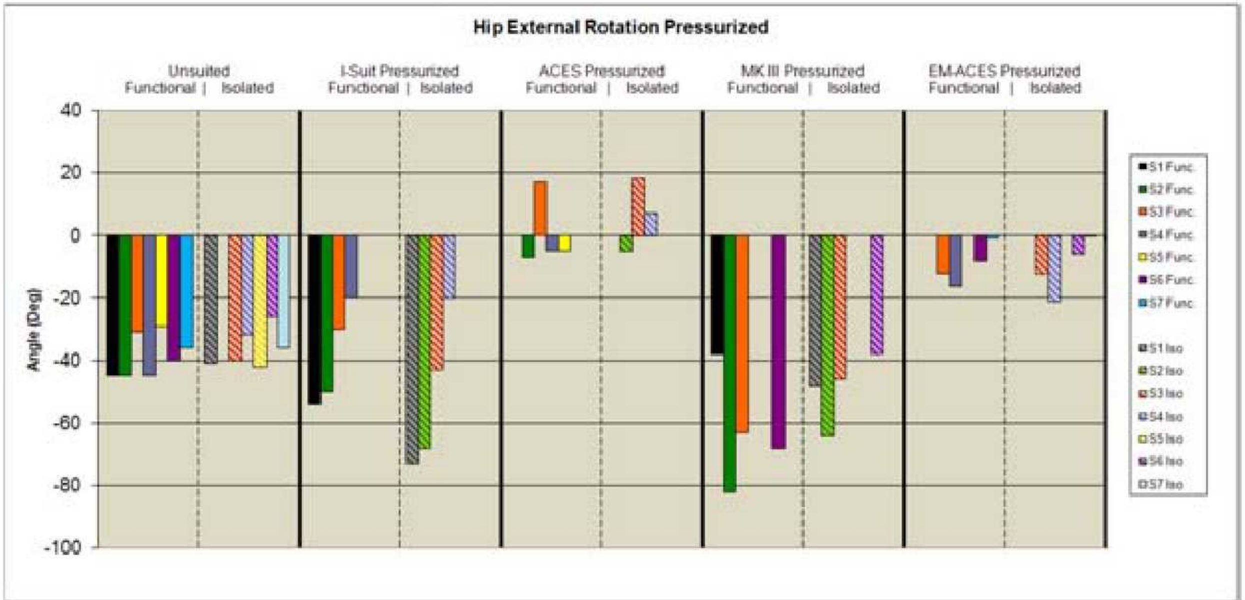


Figure 43: Hip External Rotation by Pressurized Suit, Compared across Subjects

<u>Unsuited Hip Rotation</u>

- Functional hip rotation was higher than isolated hip rotation, likely due to the combination of torso and hip rotations present in functional tasks such as cargo manipulation.

<u>ACES Hip Rotation</u>

- Even in the unpressurized case, isolated hip rotation was lower than unsuited, potentially due to fabric restrictions and a lack of bearings.

<u>MK III Hip Rotation</u>

- The MK III's hip bearings led to very high values for hip rotation. Rotation values were especially high in the functional case, where both hip and torso bearings allowed relative motion between the torso and the thigh.
- The value for hip rotation is higher than unsuited due to a difference in how the suit moves, vs. the human. The bearings allow the isolation of the suit 'hip' and the suit 'torso' - whereas unsuited, there is likely to be some sympathetic twisting of the torso as the hip is rotated. Also, if there is excess space between the inside wall of the suit and the human, subjects can rotate within the suit – a motion that is not captured when measuring the outside of the suit. It is important to remember that this study is capturing the motion of the suit – not the motion of the human within the suit.

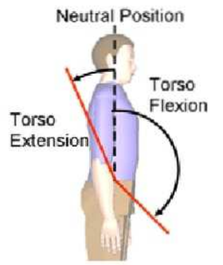
<u>I-Suit Hip Rotation</u>

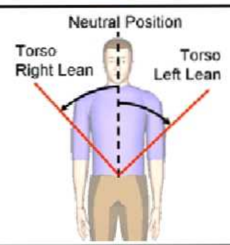
- In the isolated case, the I-suit allowed equivalent hip rotation to the MK-III. Again, the value is higher than unsuited for the same reasons as for the MK-III.

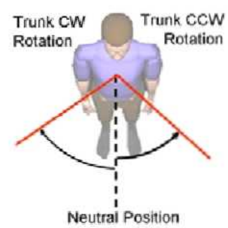
<u>EM-ACES Hip Rotation</u>

- Pressurized, the EM-ACES has minimal hip rotation due to the lack of a bearing.

Table 6: Torso Mobility







Torso	Observed Range of Motion						
		Isolated			Functional		
		Flex	Ex	Range	Flex	Ex	Range
	Unsuited All Subjects	-172	24	196	-165	15	180
	ACES Unpress	-138	44	182	-136	27	163
	ACES Press	-74	-31	42	-79	-37	42
	MK III Press	-133	32	165	-127	16	143
	I-Suit Unpress	-147	45	192	-150	15	165
	I-Suit Press	-171	39	209	-167	31	198
	EM-ACES Unpress	-137	26	163	-122	19	141
	EM-ACES Press	-47	-13	34	-56	-9	47
		Isolated			Functional		
		Rt Ln	Lft Ln	Range	Rt Ln	Lft Ln	Range
	Unsuited All Subjects	43	-46	89	25	-25	50
	ACES Unpress	41	-56	98	29	-21	50
	ACES Press	33	-8	41	19	6	13
	MK III Press	14	-16	30	32	-24	56
	I-Suit Unpress	35	-32	66	45	-15	61
	I-Suit Press	36	-21	57	41	-27	68
	EM-ACES Unpress	30	-43	72	37	-22	59
	EM-ACES Press	5	-9	14	5	-11	16
		Isolated			Functional		
		CCW	CW	Range	CCW	CW	Range
	Unsuited All Subjects	47	-57	104	30	-40	70
	ACES Unpress	50	-37	87	37	-36	73
	ACES Press	4	-12	16	0	-12	12
	MK III Press	70	-85	154	63	-45	107
	I-Suit Unpress	23	-60	83	21	-46	67
	I-Suit Press	43	-66	109	39	-40	78
	EM-ACES Unpress	42	-37	79	37	-30	66
	EM-ACES Press	9	-1	9	9	-7	16

*All Units in Degrees

The Torso

For functional purposes, the torso is analogous to the hip in terms of how joint rotations are calculated and the motions they represent.

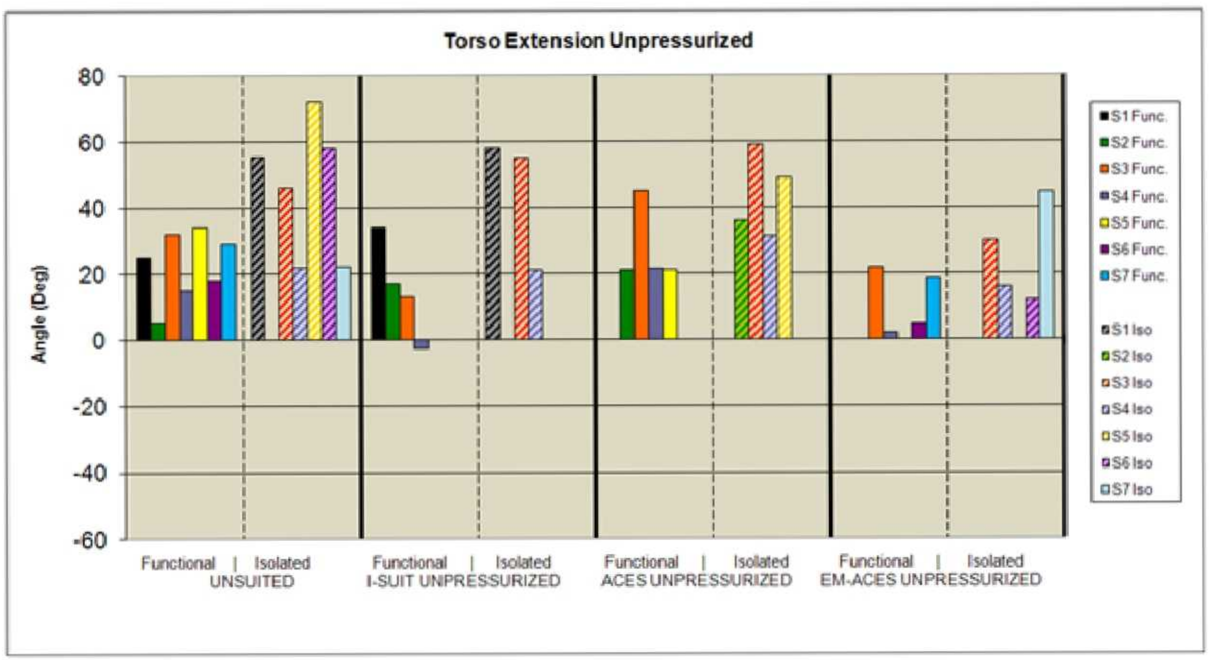


Figure 44: Torso Extension by Unpressurized Suit, Compared across Subjects

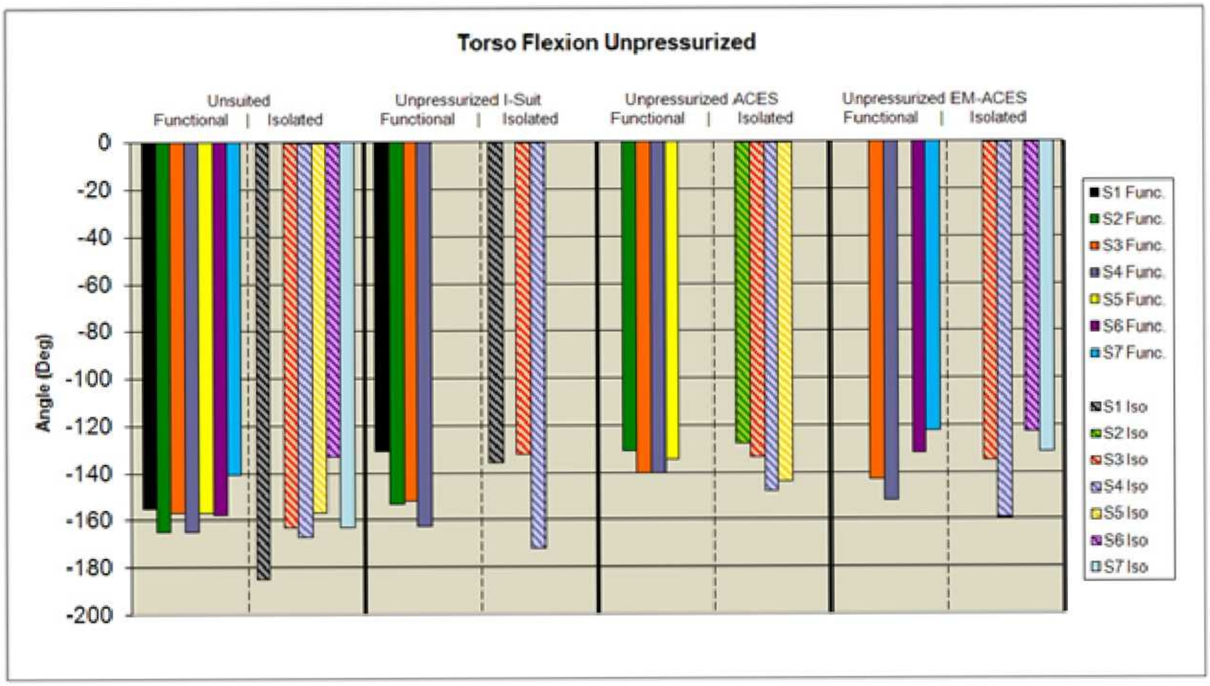


Figure 45: Torso Flexion by Unpressurized Suit, Compared across Subjects

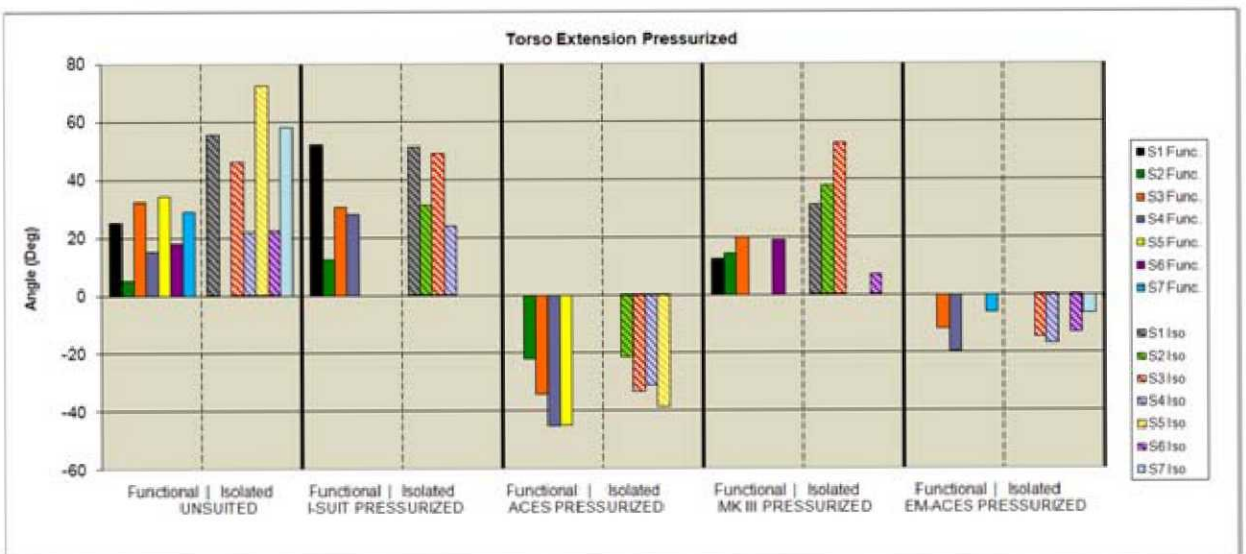


Figure 46: Torso Extension by Pressurized Suit, Compared across Subjects

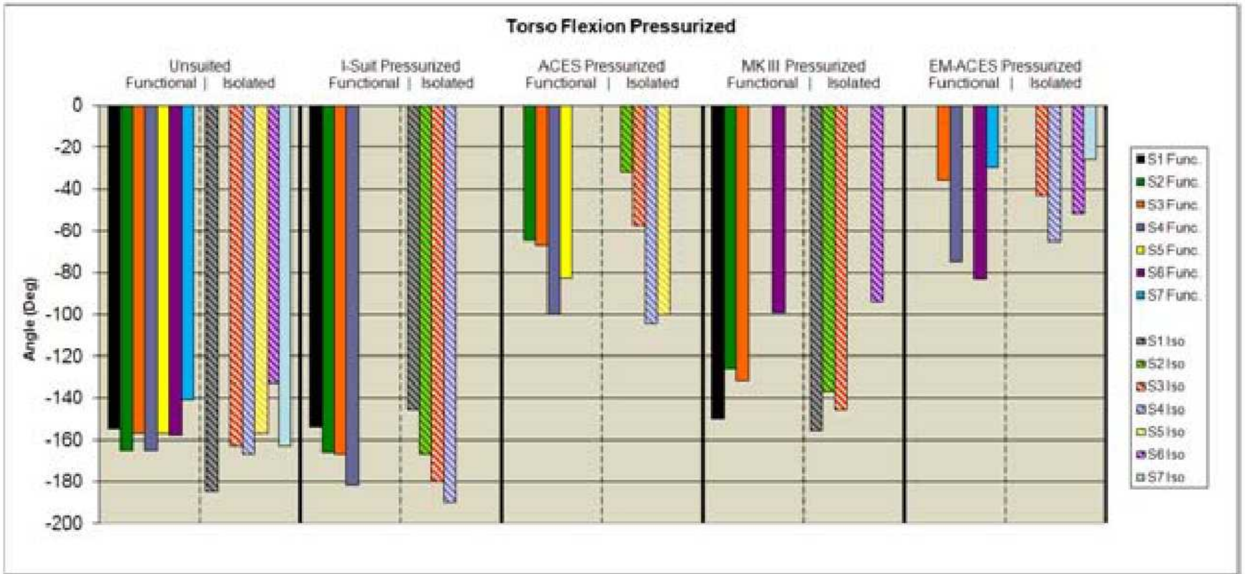


Figure 47: Torso Flexion by Pressurized Suit, Compared across Subjects

<u>Unsuited Torso Flexion</u>

- Isolated torso flexion, while similar to the hip in the manner in which it was calculated, appears higher than hip flexion because seated postures were included.

<u>ACES Torso Flexion</u>

- ACES unpressurized torso extension is high compared to the unsuited average shown, which is based on the pool of 20 subjects who completed the initial unsuited testing. However, the subjects who completed suited testing had a much higher average torso extension, in both suited and unsuited conditions, than the subjects in the unsuited testing. This holds for all suited conditions.
- The largest functional value for unpressurized torso/hip extension is due to one subject's exaggerated motion when descending a ramp – with one foot planted far behind them as they took a step.
- In the pressurized case, torso extension was never achieved by any subject in the ACES.

<u>MK III Torso Flexion</u>

- One subject's very low values for torso flexion in the MK-III skewed the average downward. The suit techs said that the torso seemed incorrectly sized for the subject, based on the subject's performance and feedback.

<u>I-Suit Torso Flexion</u>

- As previously mentioned, torso extension is high compared to the unsuited average shown, which is based on the pool of 20 subjects who completed the initial unsuited testing. Also, when leaning back in the suit, subjects were also more likely to bend their legs and throw their hips forward, altering their centers of gravity to help them lean back.
- As previously mentioned in the discussion of hip flexion, I-suit subjects could achieve very high values of torso flexion by scooting forward off of the chair and reaching for, or even behind, their ankles while squatting (see Figure 31). The subject on the right in this figure is an extreme case.

<u>EM-ACES Torso Flexion</u>

- When pressurized the EM-ACES has a more vertical stance than the pressurized ACES, which has a neutral posture featuring noticeably flexed hips. The more upright stance enables the EM-ACES to stand and walk, but not to sit, while the opposite is true for the ACES.

- The ACES and EM-ACES suits have the same total range of hip/torso flexion/extension

Figure 48: Example of Neutral Posture for ACES (Left) versus EM-ACES (Right)

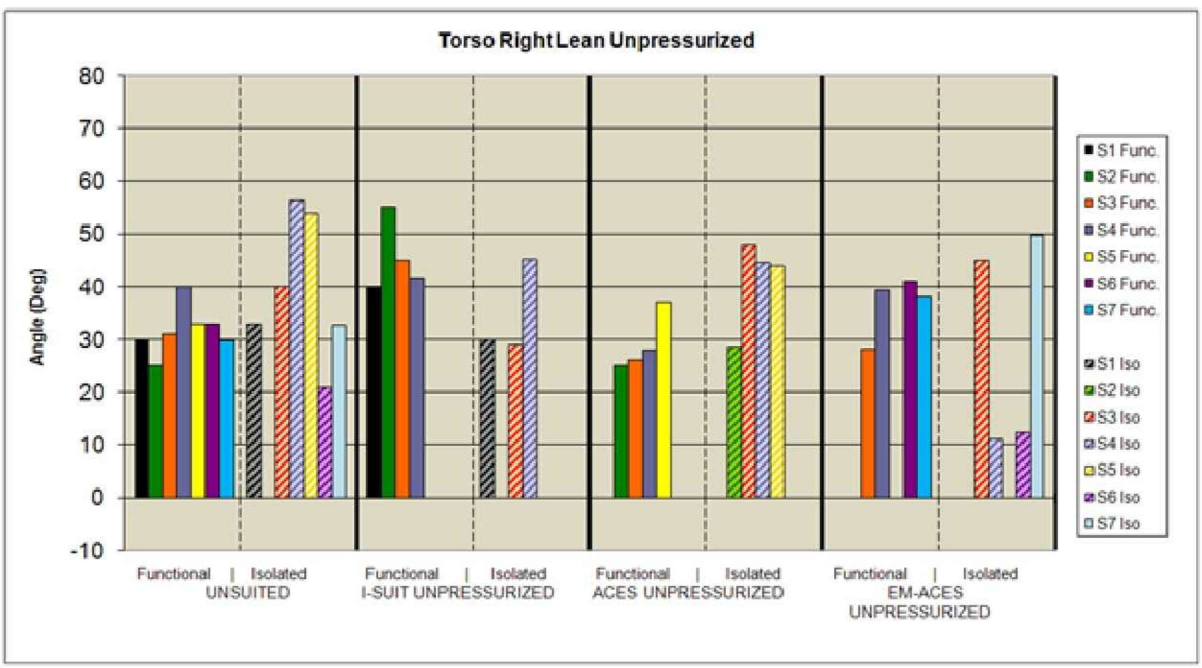


Figure 49: Torso Right Lean by Unpressurized Suit, Compared across Subjects

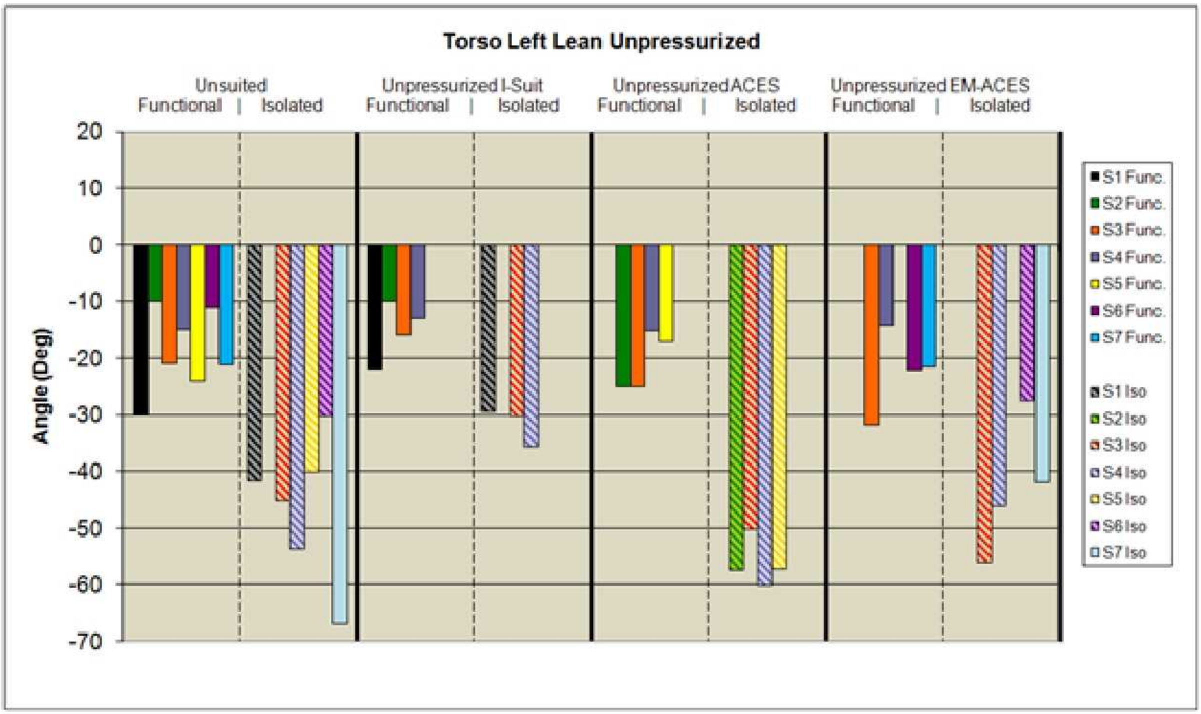


Figure 50: Torso Left Lean by Unpressurized Suit, Compared across suits

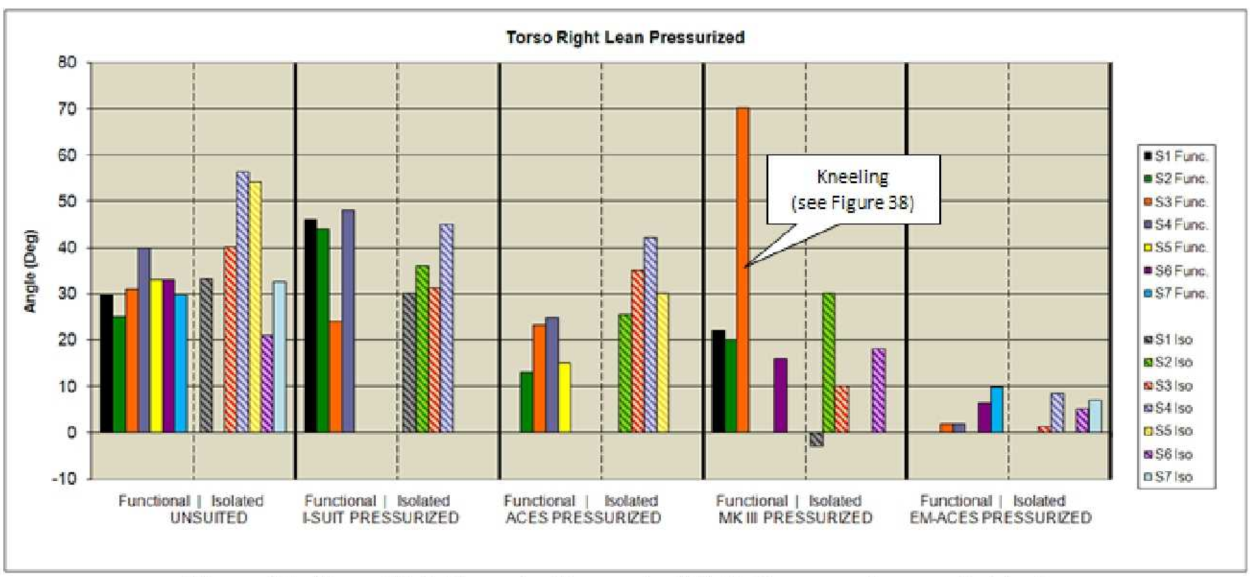


Figure 51: Torso Right Lean by Pressurized Suit, Compared across Subjects

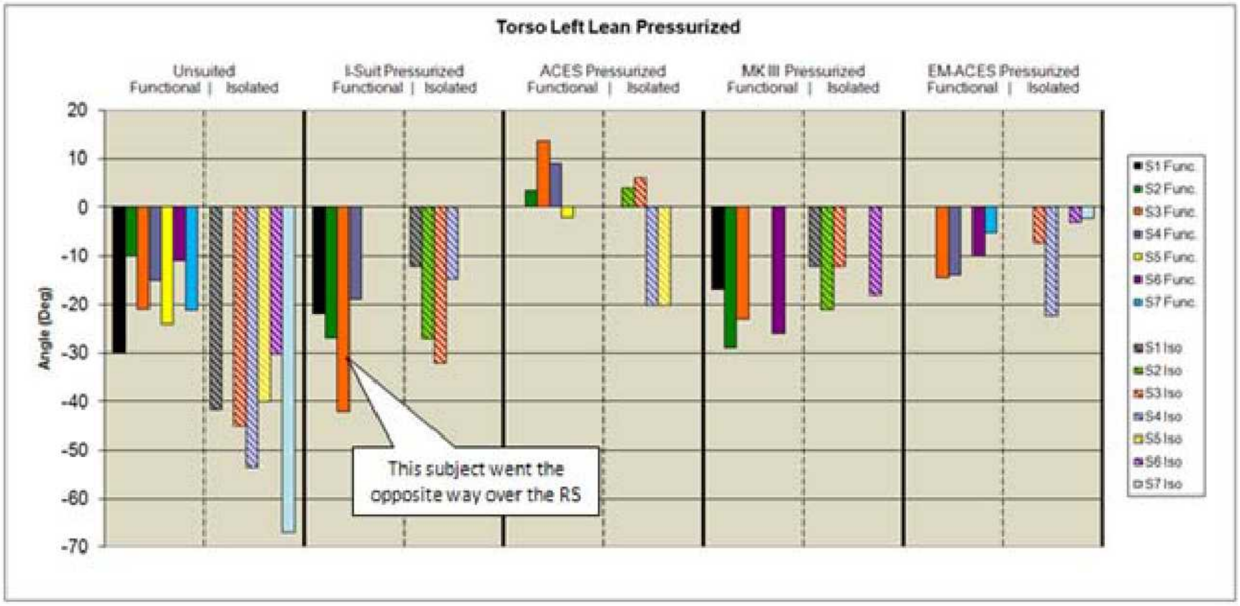


Figure 52: Torso Left Lean by Pressurized Suit, Compared across Subjects

<u>Unsuited Torso Lean</u>

- As in hip abduction/adduction, more mobility was available in an isolated instance than was utilized in any given functional task.

<u>ACES Torso Lean</u>

- The pressurized ACES had minimal lean, apart from the initial apparent lean due to the suit's splayed-leg stance

<u>MK III Torso Lean</u>

- In the isolated case, the MK-III seemed to have a low capacity for directly leaning from side to side, because the subjects could not take advantage of the MK-III's preferred movement path.
- In the functional case the suit components were allowed to move in their preferred paths, and gave significantly higher mobility.
- Only one subject performed the recumbent seat egress trial, which doubled maximum torso lean compared to the other subjects, and tended to maximize functional torso lean for I-Suit subjects.
- All subjects maximized their lean/hip abduction while kneeling on the right knee. As mentioned in the section concerning hip abduction, one subject achieved extremely high values while leaning to one side, while kneeling, in an attempt to reach the ground.

<u>I-Suit Torso Lean</u>

- The I-Suit exhibited minimal lateral lean due to lack of a dedicated joint for that purpose.

<u>EM-ACES Torso Lean</u>

- The pressurized EM-ACES had minimal lean, apart from the initial apparent lean due to the suit's natural stance

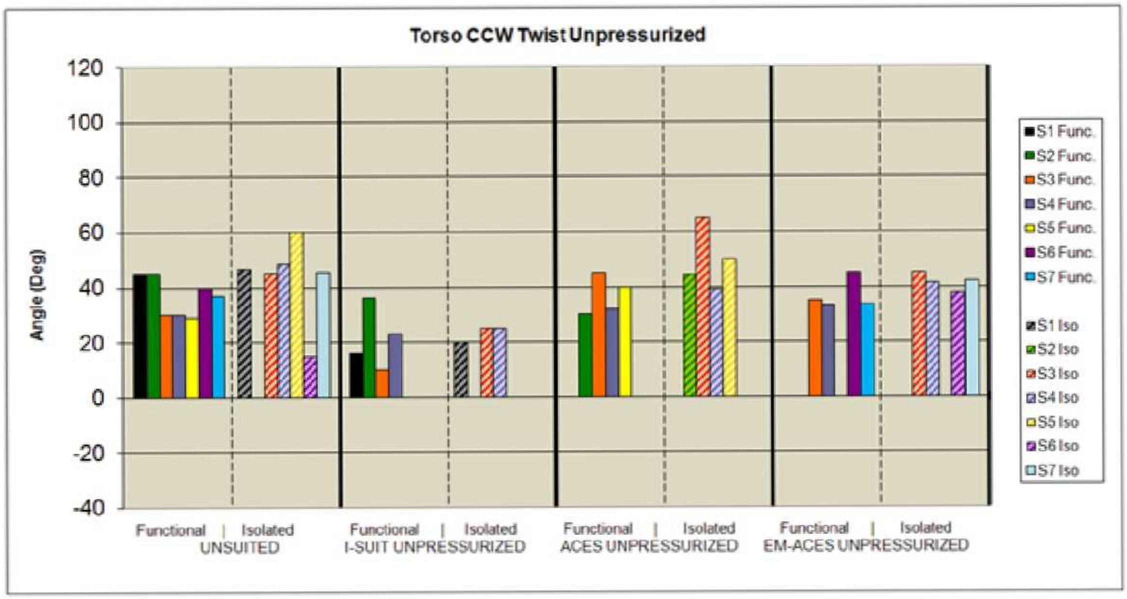


Figure 53: Torso CCW Twist by Unpressurized Suit, Compared across Subjects

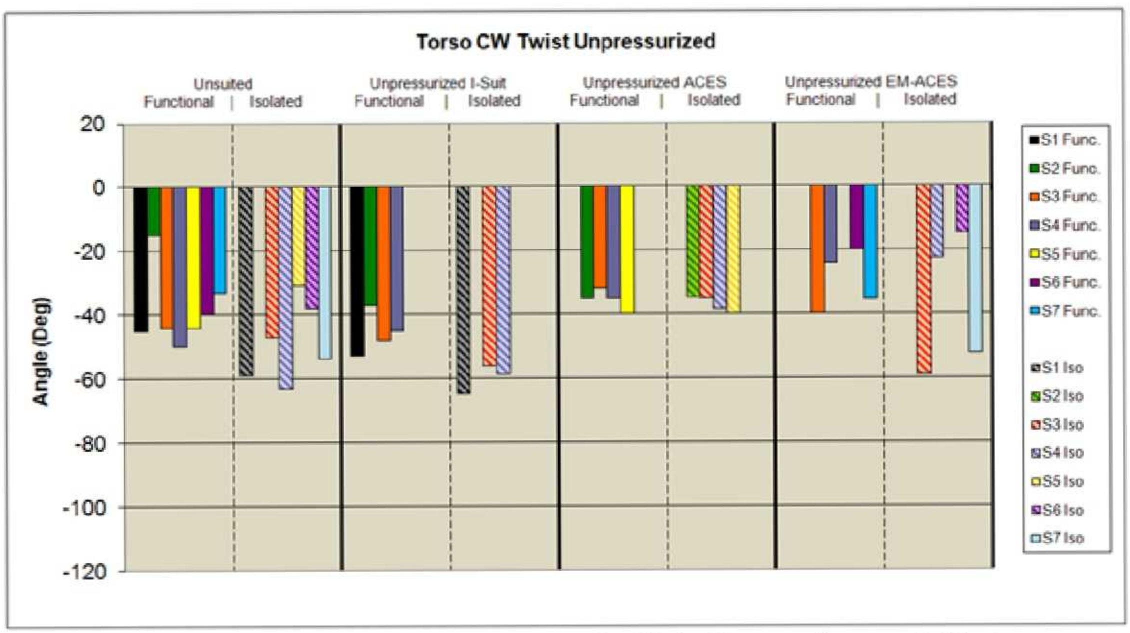


Figure 54: Torso CW Twist by Unpressurized Suit, Compared across Subjects

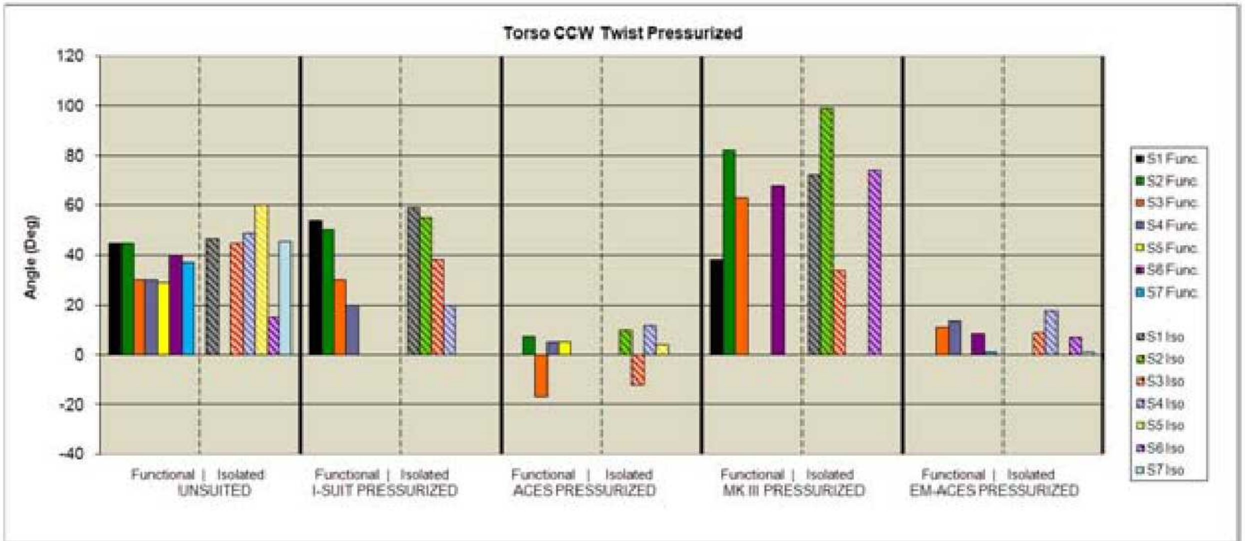


Figure 55: Torso CCW Twist by Pressurized Suit, Compared across Subjects

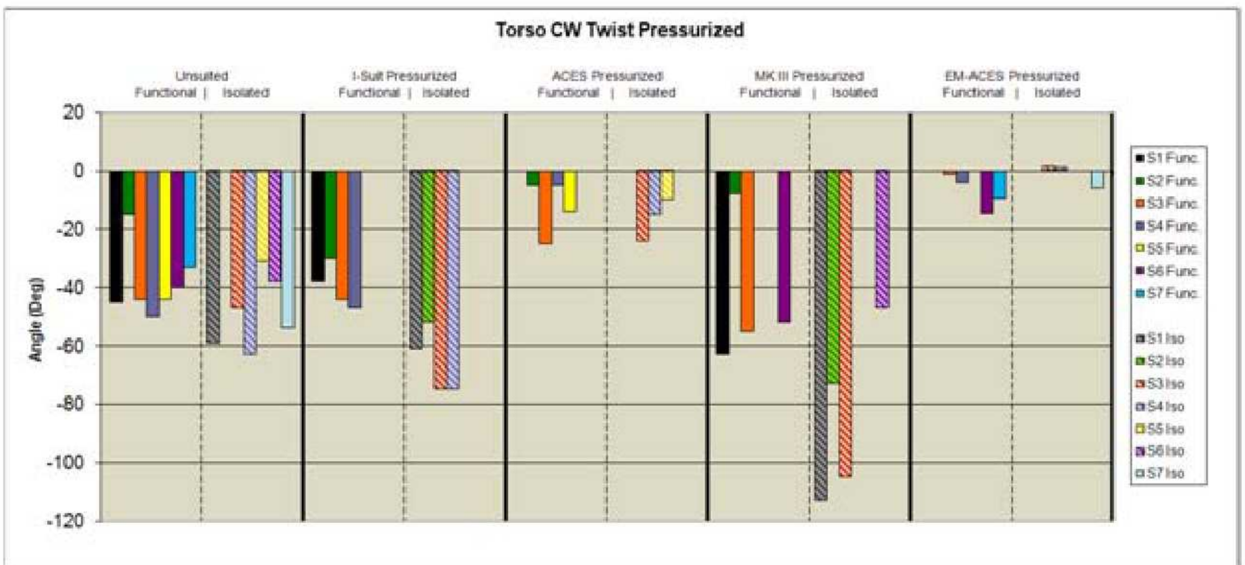


Figure 56: Torso CW Twist by Pressurized Suit, Compared across Subjects

<u>Unsuited Torso Rotation</u>

- Unsuited torso rotation demonstrated greater rotation in the isolated case, possibly because a subject is normally more likely to use other joints to complete the same motion without excessive twisting of the trunk.

<u>ACES Torso Rotation</u>

- In the unpressurized case, the ACES had an isolated torso rotation that was slightly less than unsuited, and also less than the suits with bearings.
- In the pressurized case, torso rotation was minimal, with a total range of less than 15 degrees for both isolated and functional

<u>MK III Torso Rotation</u>

- Because of the torso bearing, the MK-III achieved incredibly high isolated waist mobility (see Figure 57).

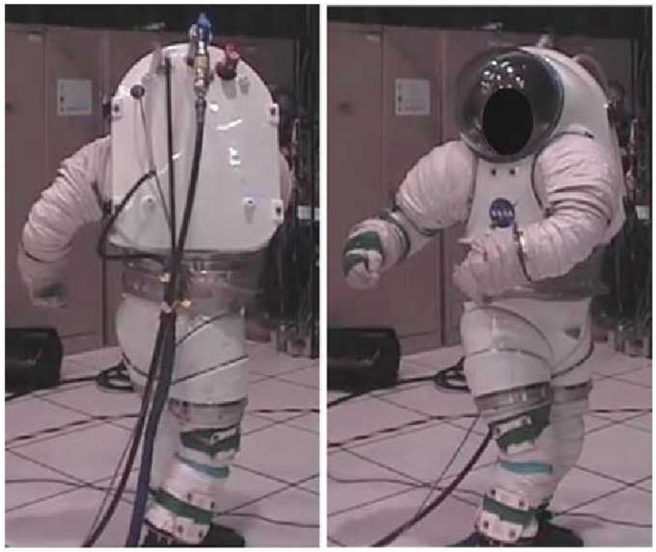


Figure 57: Torso Rotation in the MK-III

- Based on observing the tests, it seemed that this waist mobility played a large role in the motion of the suited subject, and may have countered inflexibility elsewhere.

<u>I-Suit Torso Rotation</u>

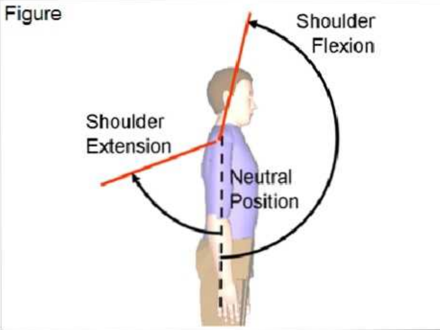
- The pressurized I-suit allowed nude-body torso rotation through its hip bearings
- The slightly lower values for torso rotation in the unpressurized I-suit were likely caused by the unpressurized suit moving with the human, whereas the human could rotate to a certain extent within the leg and torso of the pressurized suit.

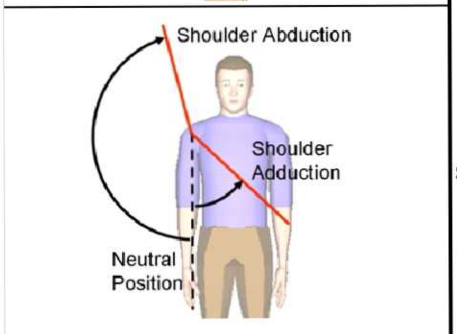
<u>EM-ACES Torso Rotation</u>

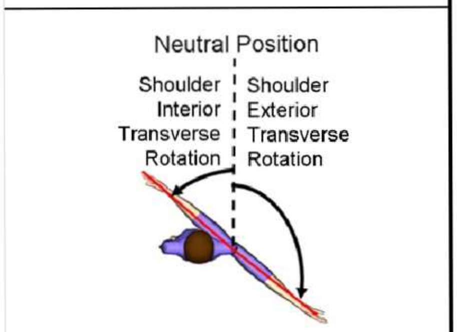
- Pressurized, the EM-ACES has minimal torso rotation due to the lack of a bearing.

Table 7: Shoulder Mobility

Figure







Shoulder

Observed Range of Motion

	Isolated			Functional		
	Flex	Ex	Range	Flex	Ex	Range
Unsuited All Subjects	166	-70	236	145	-70	215
ACES Unpress	113	-56	168	118	-60	178
ACES Press	93	-27	120	113	-44	157
MK III Press	139	-45	184	147	-71	217
I-Suit Unpress	149	-19	168	162	-44	206
I-Suit Press	148	-46	194	163	-72	235
EM-ACES Unpress	139	-50	190	153	-57	210
EM-ACES Press	176	-46	222	172	-55	227

	Isolated			Functional		
	Ab	Ad	Range	Ab	Ad	Range
Unsuited All Subjects	-154	43	196	-105	35	140
ACES Unpress	-105	22	127	-110	25	135
ACES Press	-90	-6	83	-106	-15	91
MK III Press	-138	21	158	-120	26	146
I-Suit Unpress	-160	34	194	-165	37	202
I-Suit Press	-140	7	147	-173	12	185
EM-ACES Unpress	-142	29	170	-126	21	147
EM-ACES Press	-142	-16	125	-125	-20	105

*All Units in Degrees

	Isolated			Functional		
	Int Rot	Ext Rot	Range	Int Rot	Ext Rot	Range
Unsuited (7) Subjects	41	-133	174	46	-121	168
ACES Unpress	17	-144	161	25	-126	150
ACES Press	-23	-120	98	-9	-123	115
MK III Press	31	-105	136	31	-97	128
I-Suit Unpress	35	-88	124	43	-87	130
I-Suit Press	11	-118	129	21	-122	143
EM-ACES Unpress	19	-115	135	23	-121	144
EM-ACES Press	-16	-114	97	-11	-118	107

*All Units in Degrees

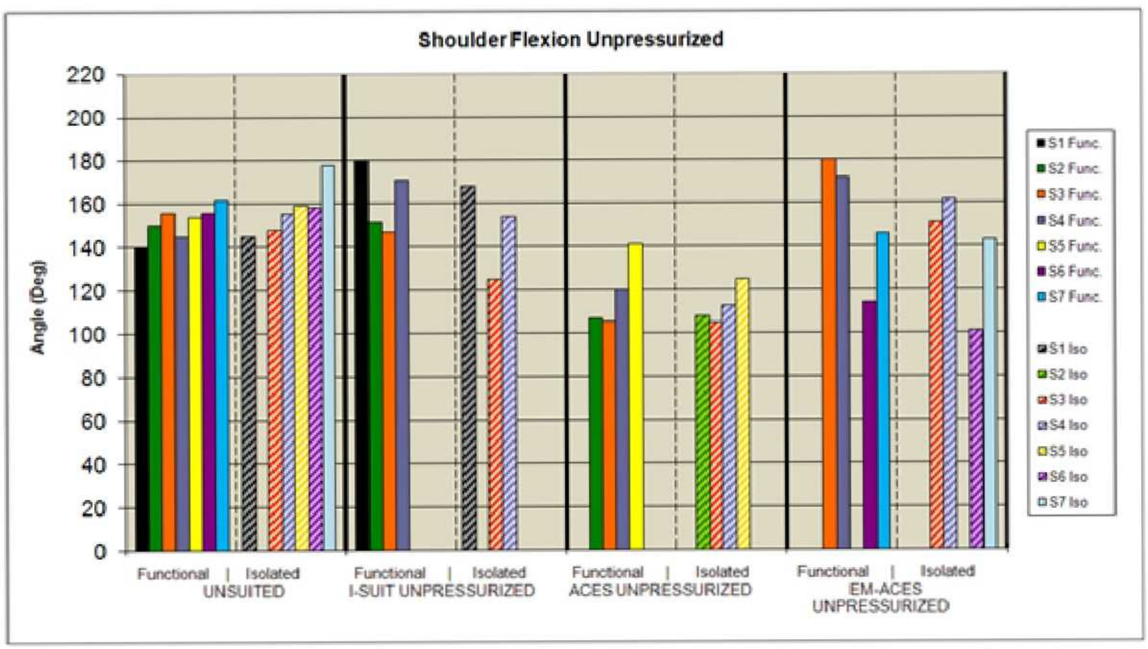


Figure 58: Shoulder Flexion by Unpressurized Suit, Compared across Subjects

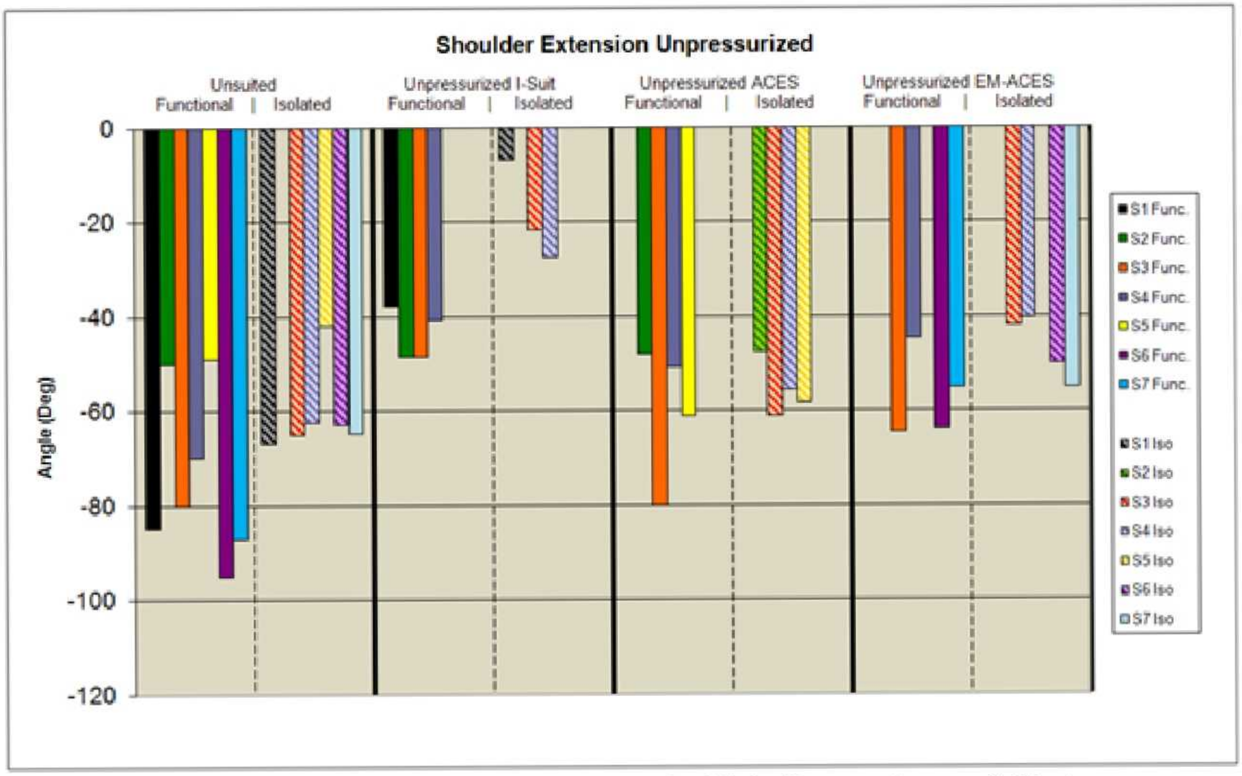


Figure 59: Shoulder Extension by Unpressurized Suit, Compared across Subjects

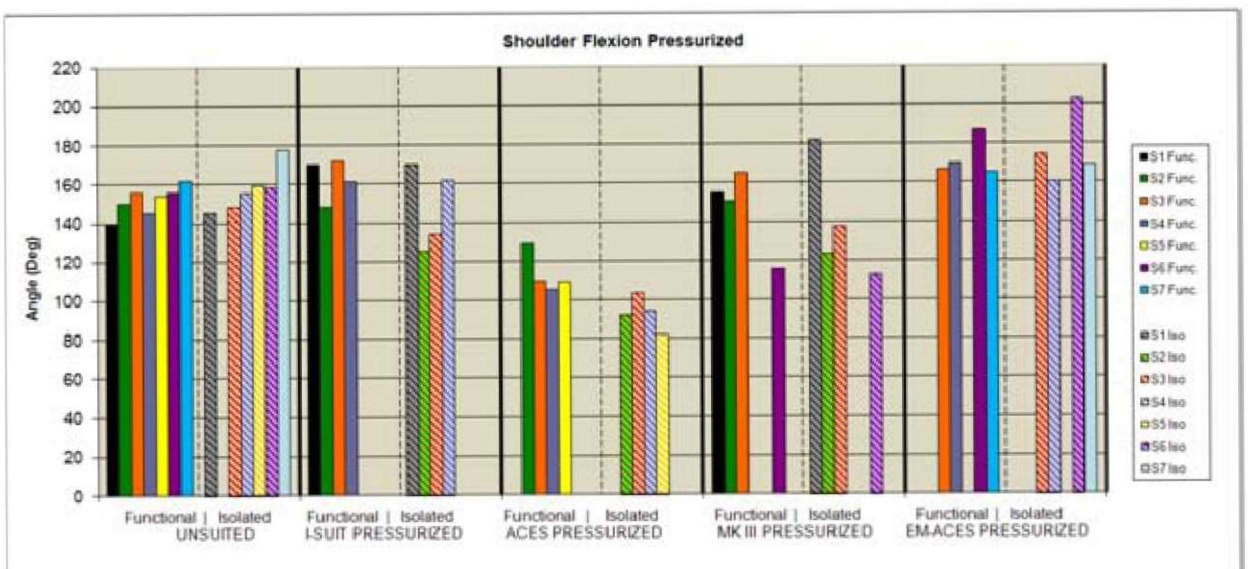


Figure 60: Shoulder Flexion by Pressurized Suit, Compared across Subjects

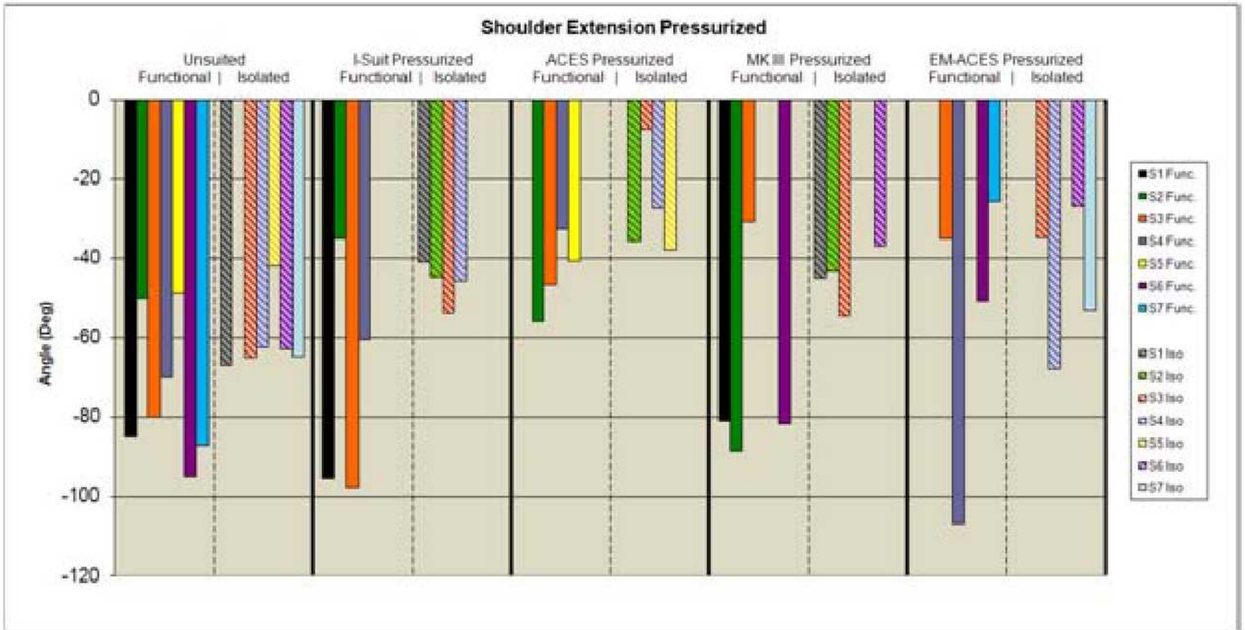


Figure 61: Shoulder Extension by Pressurized Suit, Compared across Subjects

The Shoulder

Like the hip joint, the shoulder is a complex, multiple axis joint that may be accommodated in a suit by a series of mobility joints whose geometry may sometimes result in varied movement dynamics that are not completely analogous to human motions.

Unsuited Shoulder Flexion

- Isolated shoulder range of motion was greater than functional shoulder motion in all cases except in extension, where the joint hit the physiological limit.

ACES Shoulder Flexion

- Subject feedback and examination of video (Figure 62) of shoulder flexion in the unpressurized ACES suggests an obvious restriction in motion when reaching overhead, as fabric pulls taut. This restriction is likely caused by a combination of limited fabric relief in the suit, and the bands that hold the marker plates in place, since slack fabric is essentially wrapped tight against the subject.

Figure 62: Shoulder Flexion: Unsuited vs. Unpressurized ACES

MK III Shoulder Flexion

- Only one subject completed the recumbent seat trials in the MK III, and these tended to maximize shoulder flexion, and always maximized shoulder extension in the I-suit.

- Climbing down the ladder facing forward tended to maximize shoulder extension.

I-Suit Shoulder Flexion

- In the functional case, suited shoulder flexion was occasionally higher than unsuited. This could have been a result of a variety of factors, the most likely of which are:
    1. Subjects shifting within the suit
    2. The subjects moving their own arm out of the saggital plane – which would have been noted in an unsuited trial, but cannot always be judged when the subject is wearing a suit
    3. The heavy suit limb dragging their arm back when they reach behind them in the recumbent position.
- The following graphic (Figure 63) is a good example of shoulder flexion in the suit being higher than unsuited.

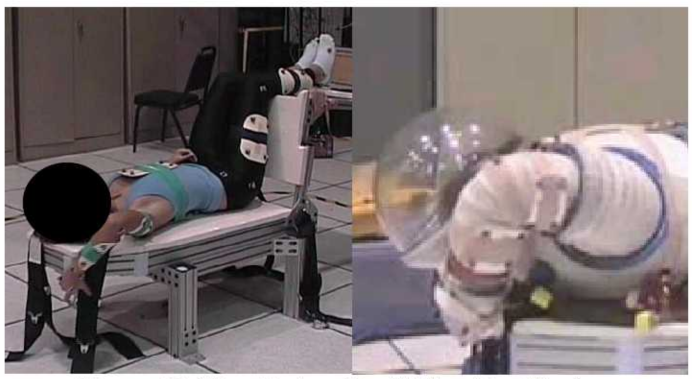


Figure 63: Unsuited vs. I-suit Shoulder Flexion

- The pressurized I-suit often had large values of shoulder extension associated with the recumbent seat. Subjects generally had their arms hanging over the sides of the seat when in a neutral posture. One subject mentioned that this position was more comfortable than trying to hold the suit arms in place in front of them. Three out of the four subjects maximized shoulder extension while attempting to egress the seat.

EM-ACES Shoulder Flexion

- Even unpressurized, the EM-ACES had a 20% higher shoulder flexion/extension range available than the unpressurized ACES, and had a comparable range to the unpressurized I-suit.
- Pressurized, the EM-ACES had a comparable range of shoulder flexion-extension to the I-suit

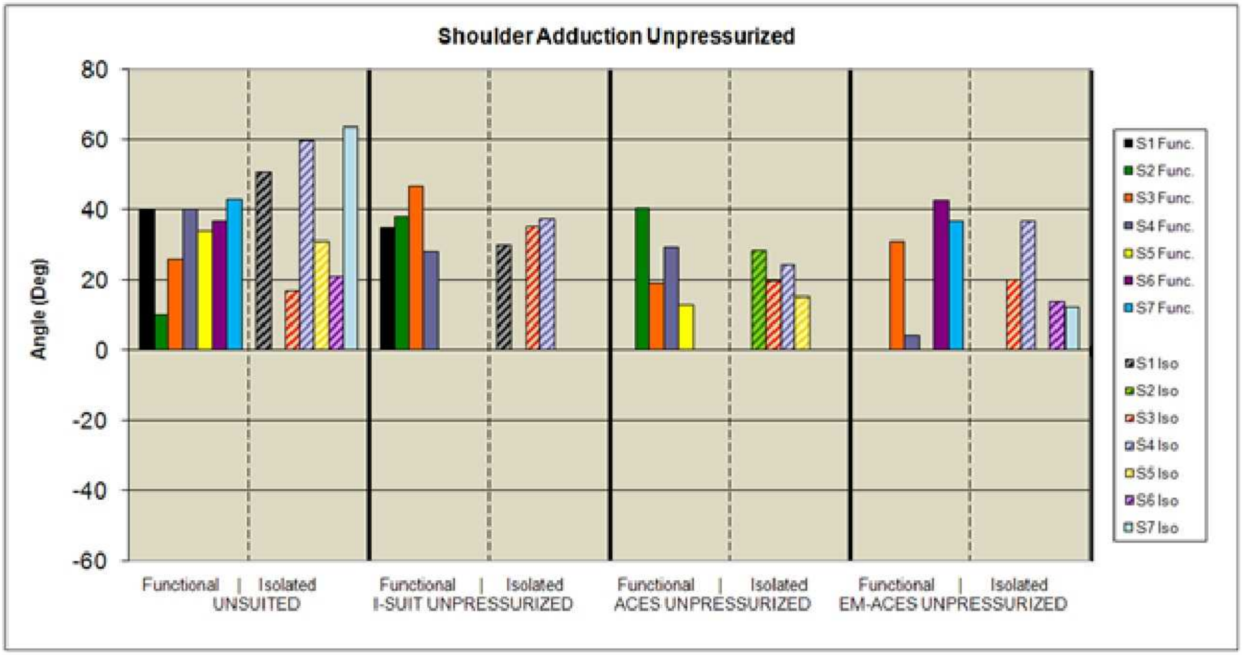


Figure 64: Shoulder Adduction by Unpressurized Suit, Compared across Subjects

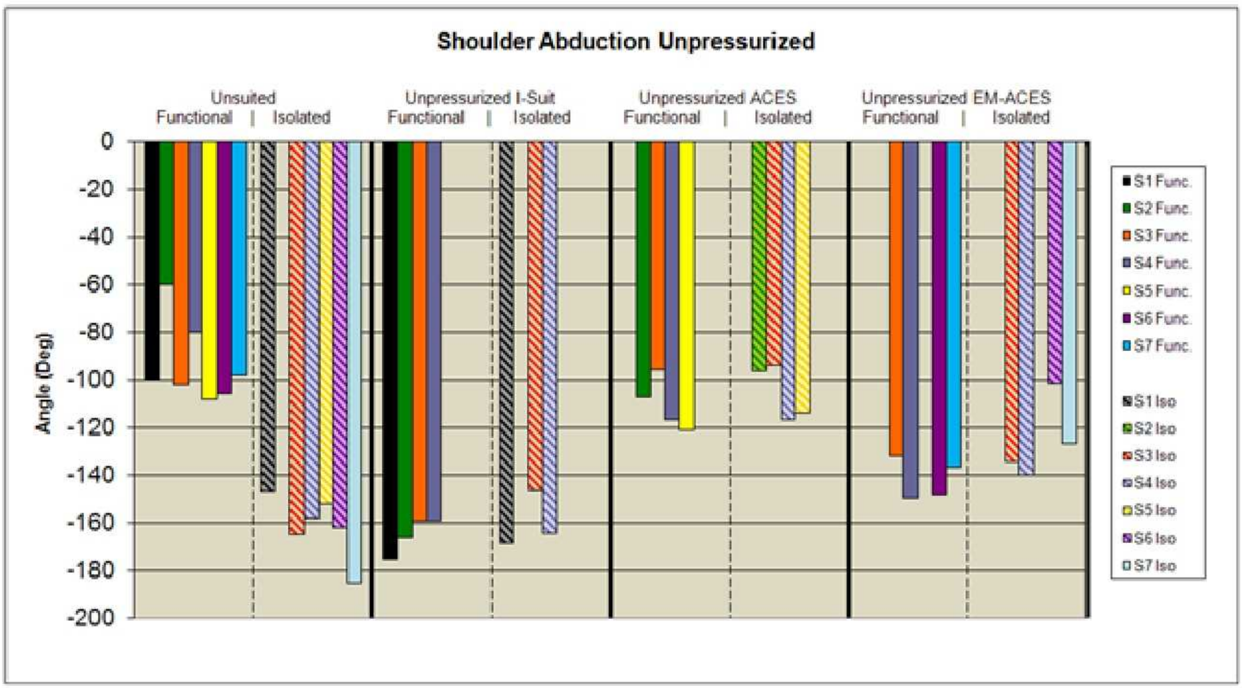


Figure 65: Shoulder Abduction by Unpressurized Suit, Compared across Subjects

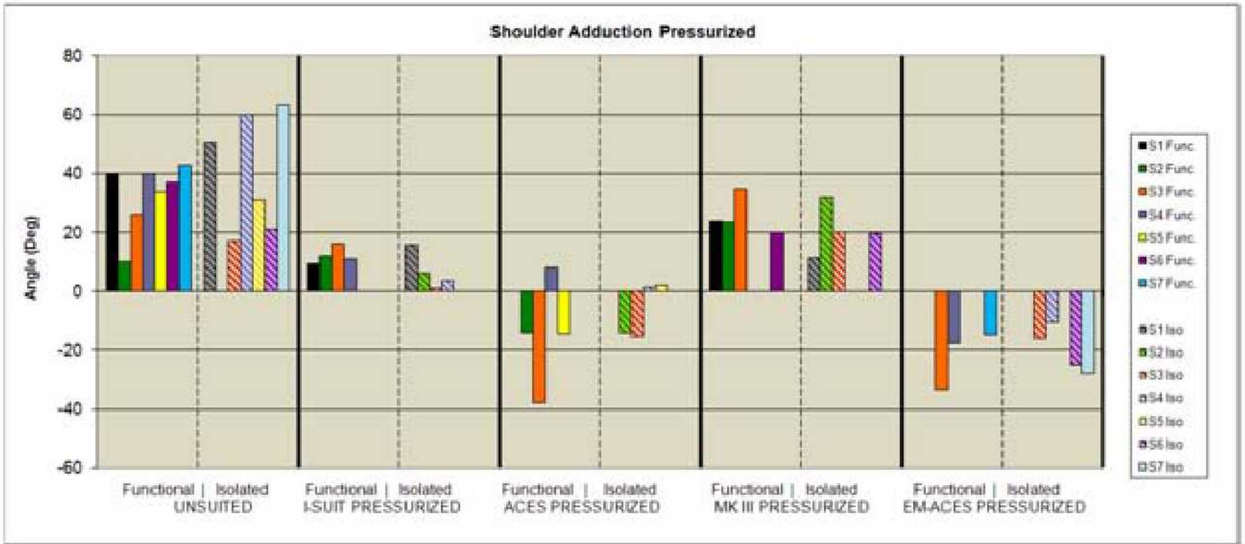


Figure 66: Shoulder Adduction by Pressurized Suit, Compared across Subjects

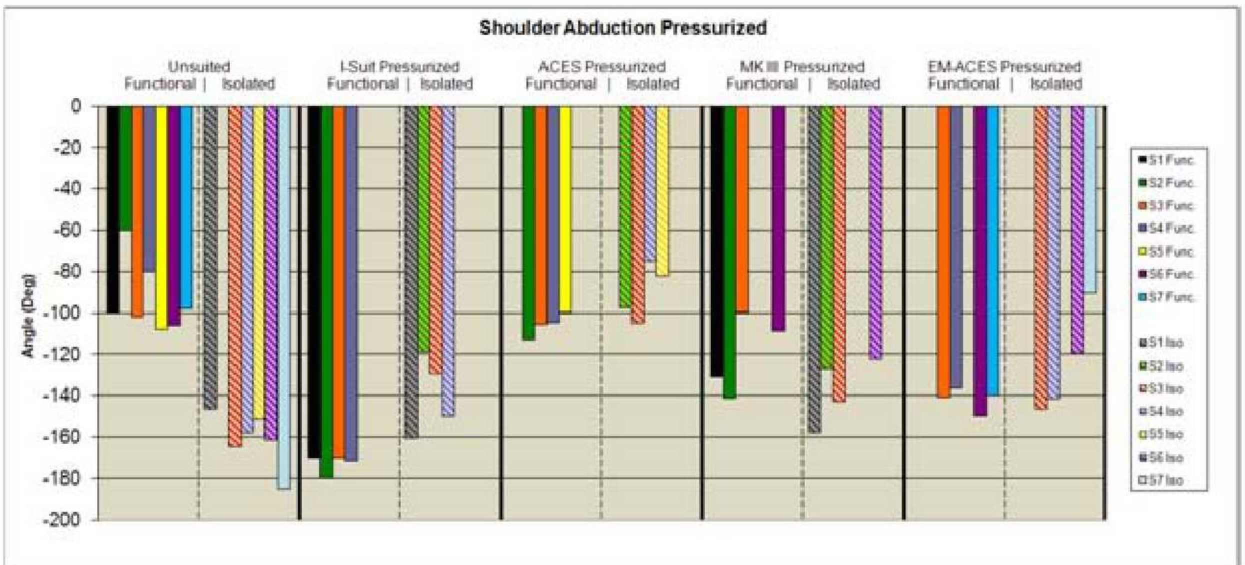


Figure 67: Shoulder Abduction by Pressurized Suit, Compared across Subjects

<u>Unsuited Shoulder Abduction</u>

- Unsuited shoulder abduction is a good example of functionally necessary mobility being substantially less than what is achieved in the isolated task.

<u>ACES Shoulder Abduction</u>

- For the isolated case, the unpressurized ACES had the lowest abduction/adduction range of any condition besides the pressurized ACES. Again, the wrappings on the plates seemed to cause a noticeable restriction in shoulder mobility.
- For an example of reduced shoulder abduction in the unpressurized ACES, see Figure 68, which shows the subject attempting to maximize shoulder abduction in the arm that has been wrapped (left) compared to the unwrapped arm (right).

Figure 68: Abduction in the unpressurized ACES: Wrapped (Right) vs. Unwrapped (Left)

MK III Shoulder Abduction

- For the functional case, the MK III had a higher functional range of motion than unsuited. This is because the definition of abduction can break down in suited conditions due to altered movement strategies, including coupling of abduction and flexion of the shoulder.

I-Suit Shoulder Abduction

- The bulk of the suit made it very difficult for a subject to cleanly adduct their arm across their chest
- High values for abduction in the functional case are a reflection of the movement strategies adopted in the suit: the arm was rarely purely flexed or abducted – a combination of these motions was generally needed to lift the arm above the head.

EM-ACES Shoulder Abduction

- The unpressurized EM-ACES didn't see the same apparent reduction in abduction seen in the ACES – again, this could have been a result of fabric relief allowed by the bearing, and preventing the type of wrapping-induced restriction that was indicated in the ACES

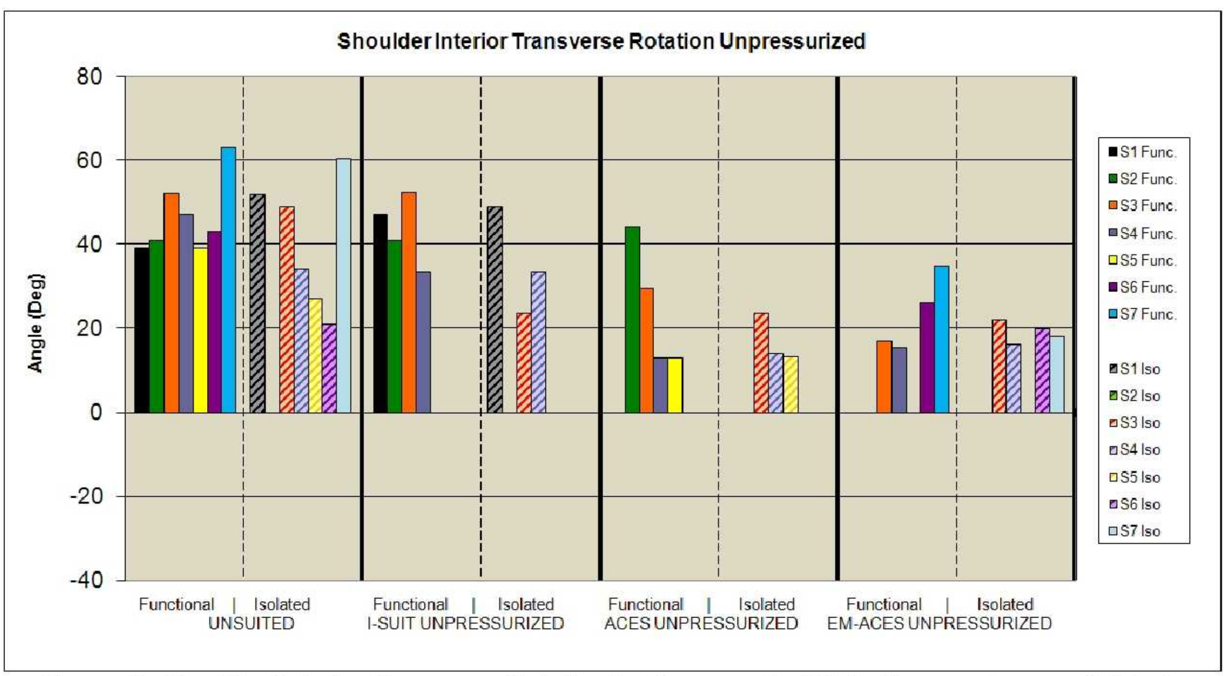


Figure 69: Shoulder Interior Transverse Rotation by Unpressurized Suit, Compared across Subjects

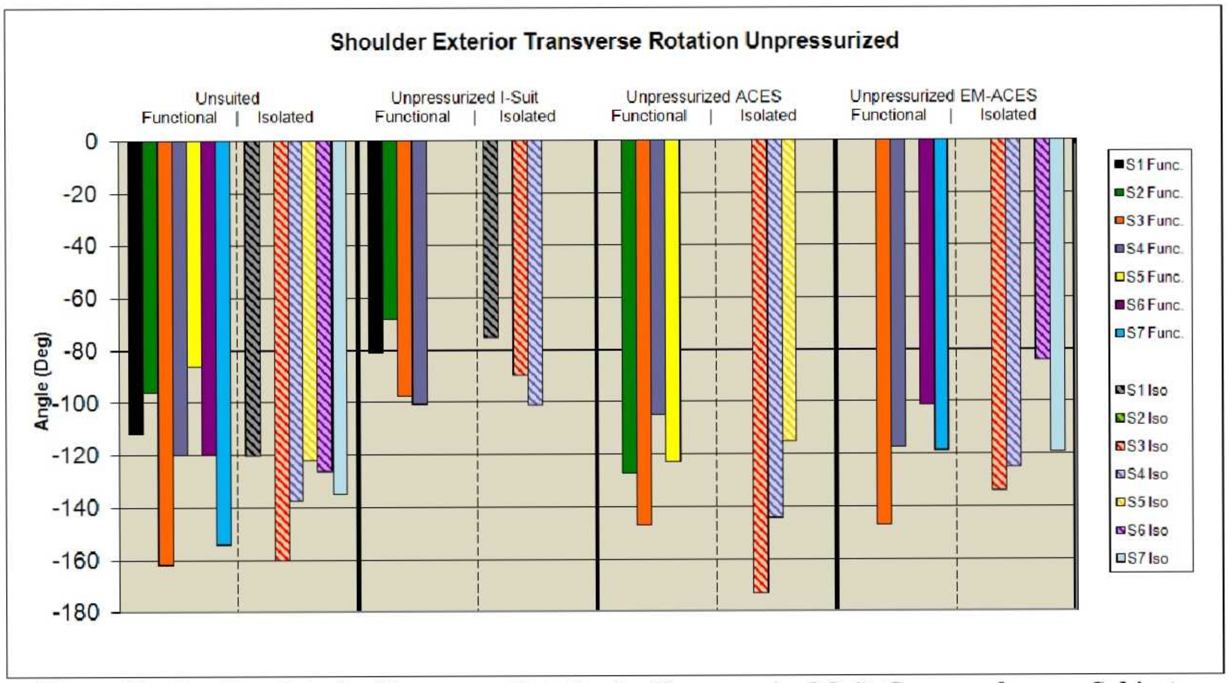


Figure 70: Shoulder Exterior Transverse Rotation by Unpressurized Suit, Compared across Subjects

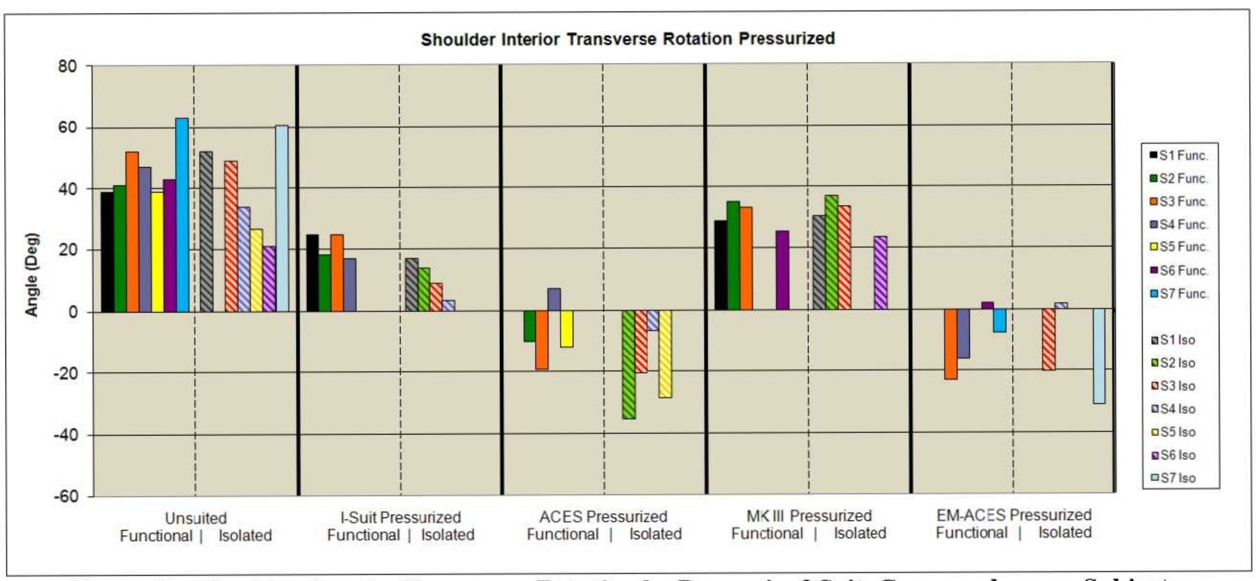


Figure 71: Shoulder Interior Transverse Rotation by Pressurized Suit, Compared across Subjects

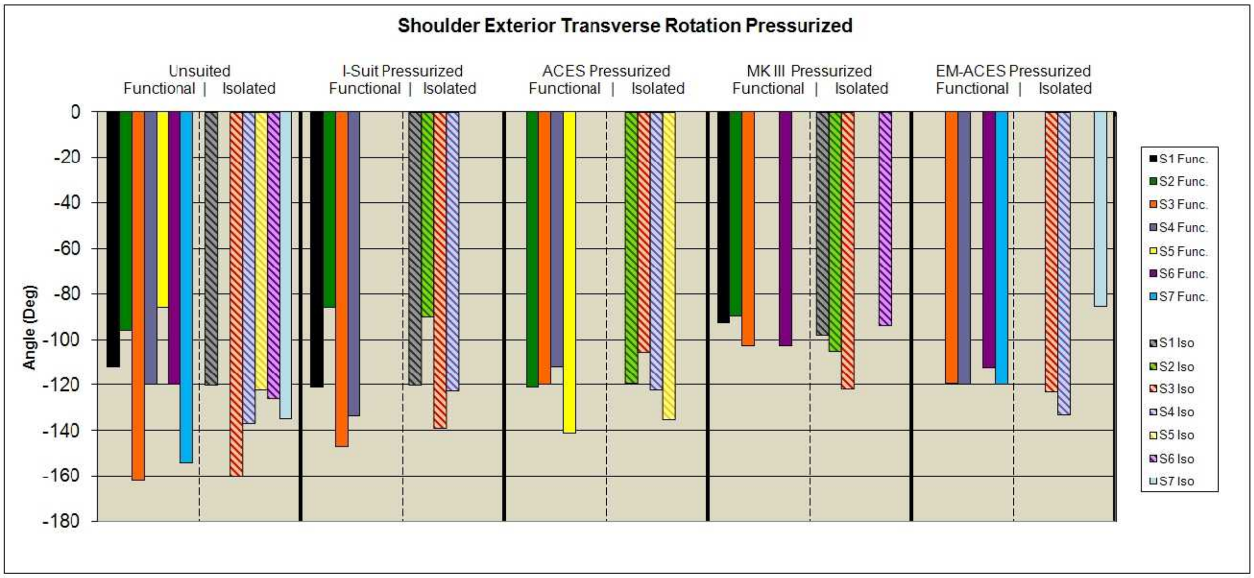


Figure 72: Shoulder Exterior Transverse Rotation by Unpressurized Suit, Compared across Subjects

Unsuited Shoulder Transverse Rotation

- This motion was not evaluated for earlier unsuited trials, so data is only available for the seven subjects who completed the same protocol while suited (as indicated in the table).

ACES Shoulder Transverse Rotation

- Unpressurized, the ACES has the highest shoulder transverse rotation range of any of the suits
- Pressurized, the ACES could not reach across the body in the transverse plane (had a negative maximum interior transverse rotation), but matched unsuited values in exterior rotation.

MK-III Shoulder Transverse Rotation

- The pressurized MK-III shoulder restricted the subject in reaching back (exterior transverse rotation), but achieved nearly unsuited values in interior transverse rotation

I-Suit Shoulder Transverse Rotation

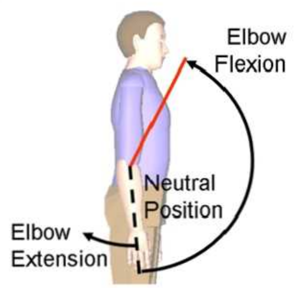
- Like the ACES, the pressurized I-suit matched unsuited values in exterior transverse rotation, but was restricted in interior transverse rotation.

EM-ACES Shoulder Transverse Rotation

- Pressurized, the EM-ACES shoulder performed similarly to the ACES in transverse rotation.
- Unpressurized, the EM-ACES had a slightly lower range of transverse rotation than the ACES

Table 8: Elbow Mobility

Figure



		Observed Range of Motion					
		Isolated			Functional		
		Flex	Ex	Range	Flex	Ex	Range
	Unsuited All Subjects	148	0	148	130	0	130
	ACES Unpress	125	9	116	127	12	116
Elbow	ACES Press	125	19	106	119	8	111
	MK III Press	113	18	96	110	20	90
	I-Suit Unpress	79	0	79	97	2	95
	I-Suit Press	104	3	101	99	0	100
	EM-ACES Unpress	105	6	99	117	0	117
	EM-ACES Press	135	22	113	128	10	118

*All Units in Degrees

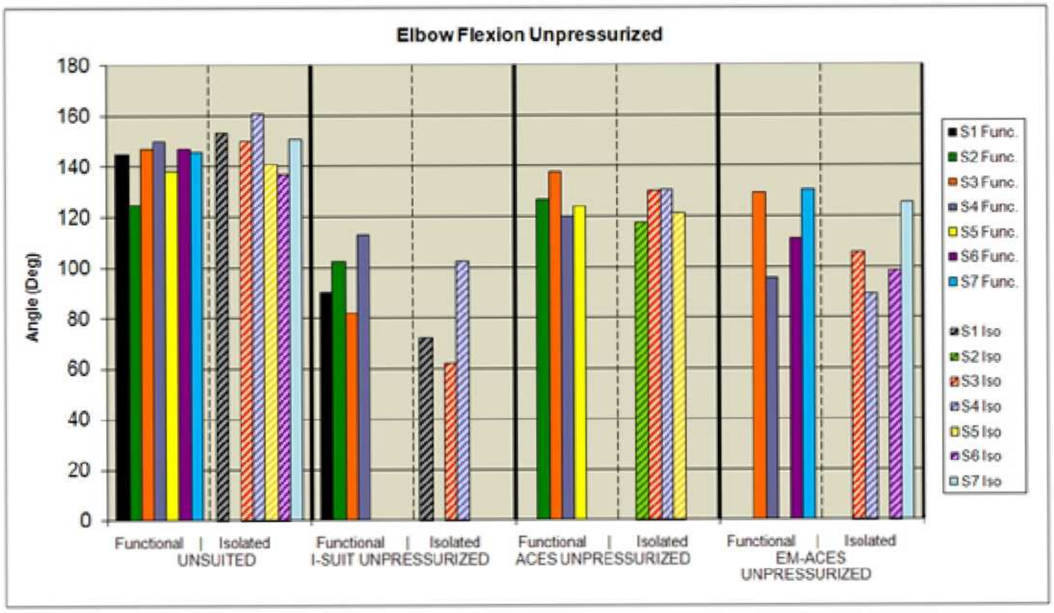


Figure 73: Elbow Flexion by Unpressurized Suit, Compared across Subjects

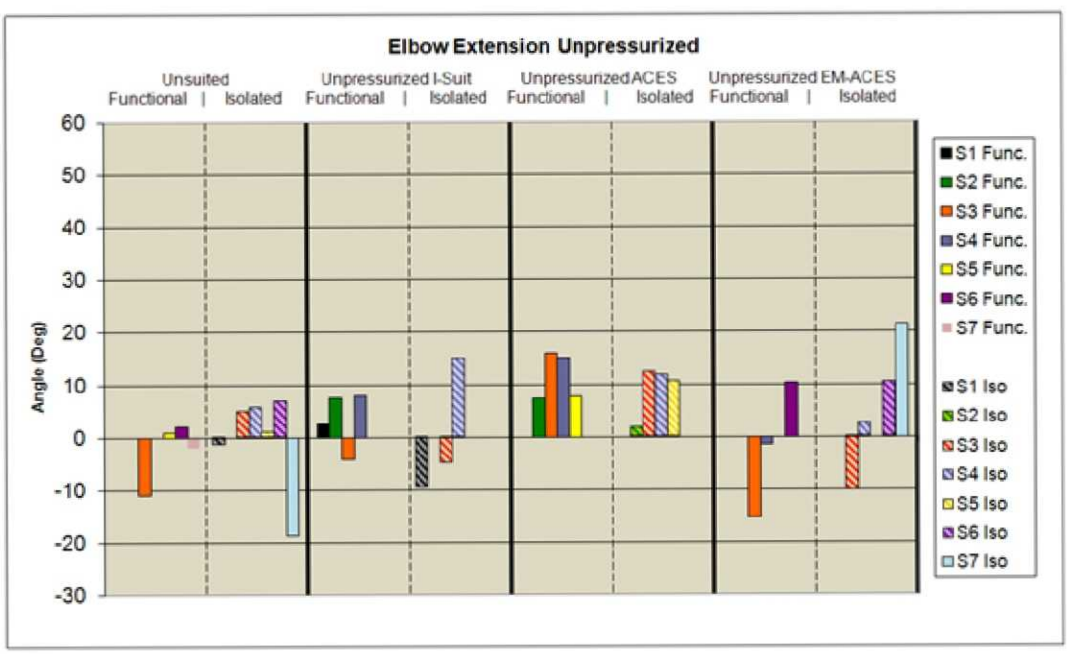


Figure 74: Elbow Extension by Unpressurized Suit, Compared across Subjects

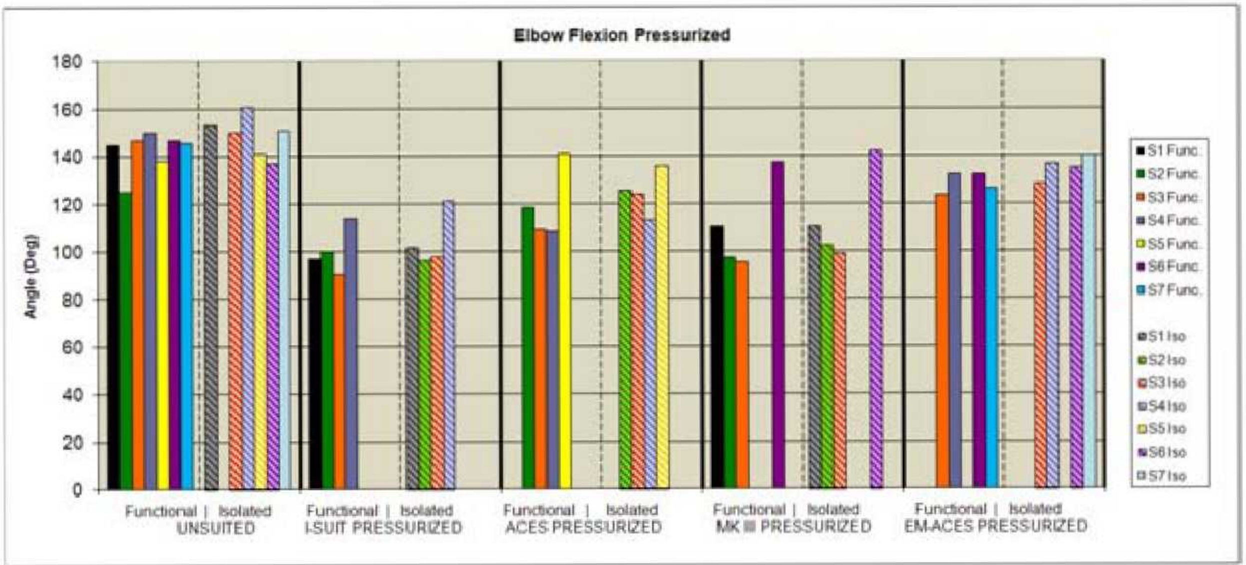


Figure 75: Elbow Flexion by Pressurized Suit, Compared across Subjects

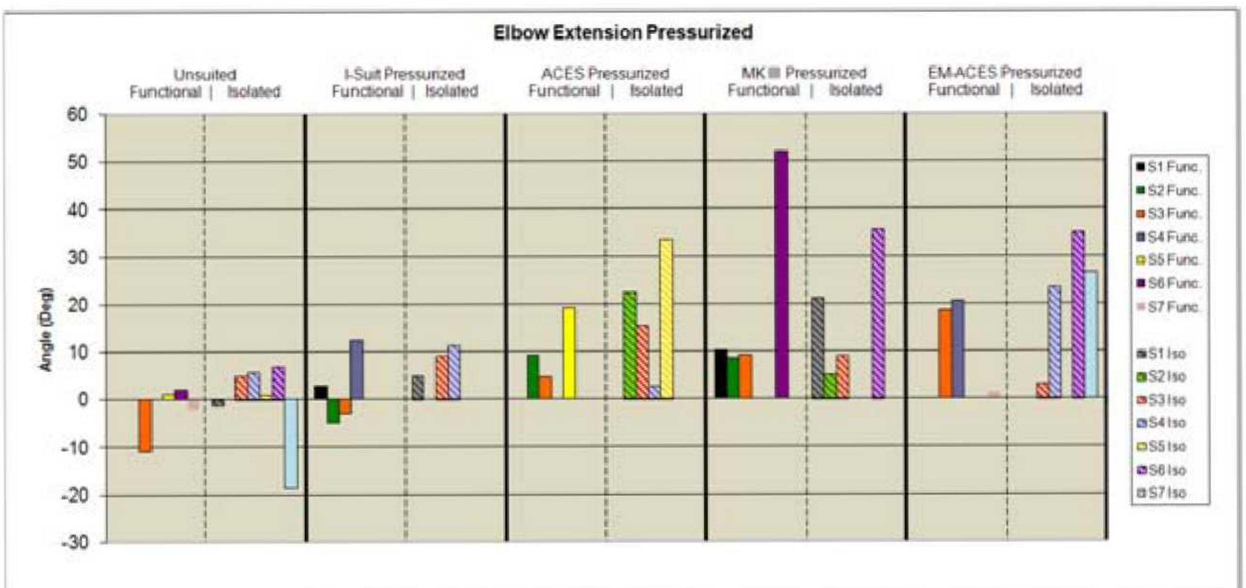


Figure 76: Elbow Extension by Pressurized Suit, Compared across Subjects

The Elbow

The mobility of the elbow joint is higher when unsuited than in any suited condition.

<u>Unsuited Elbow Flexion</u>

- Isolated elbow flexion was generally higher than functional.

<u>ACES Elbow Flexion</u>

- In the pressurized case, the elbow has a bias towards flexion (see Figure 77)

Figure 77: Pressurized ACES Elbow Bias

MK III Elbow Flexion

- The MK III had a slight bias towards flexion. However, this value was likely skewed by one subject, who never straightened their arm completely.

I-Suit Elbow

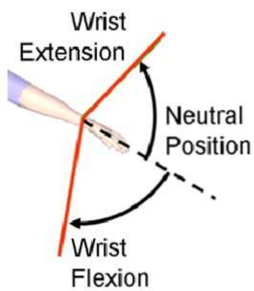
- When unpressurized, the I-suit elbow had a lower isolated range of motion than any other suit. This may have been caused by hardware-on-hardware contact, since the upper arm bearing slips down when the suit is unpressurized, allowing it to come in contact with the wrist bearing when a subject flexes their elbow.

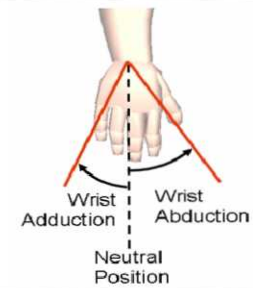
EM-ACES Elbow

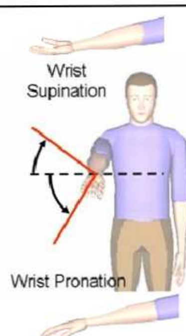
- Although the EM-ACES introduced a bicep bearing, it did not seem to have a major impact on unpressurized elbow flexion mobility. Some arm bearing to wrist bearing contact was apparent, and could have contributed to the slightly lower elbow flexion values compared to the ACES. However, this reduction may also have been a factor of the upper arm plate slipping down.
- Pressurized elbow flexion mobility was comparable to ACES elbow mobility.

Table 9: Wrist Mobility

Figure







Wrist

Observed Range of Motion						
	Isolated			Functional		
	Ex	Flex	Range	Ex	Flex	Range
Unsuited All Subjects	-80	62	142	-85	60	145
ACES Unpress	-66	79	145	-92	50	141
ACES Press	-65	73	138	-45	57	102
MK III Press	-35	65	100	-51	52	103
I-Suit Unpress	-58	84	141	-84	57	141
I-Suit Press	-44	76	120	-63	57	120
EM-ACES Unpress	-47	78	125	-73	66	139
EM-ACES Press	-40	71	111	-64	46	110
	Isolated			Functional		
	Ab	Ad	Range	Ab	Ad	Range
Unsuited All Subjects	-32	21	53	-30	25	55
ACES Unpress	-29	30	59	-30	33	63
ACES Press	-31	39	70	-35	36	70
MK III Press	-17	28	45	-34	24	59
I-Suit Unpress	-33	34	67	-26	39	65
I-Suit Press	-18	28	46	-22	32	54
EM-ACES Unpress	-29	32	61	-26	31	57
EM-ACES Press	-31	24	55	-39	29	68
	Isolated			Functional		
	Pro	Sup	Range	Pro	Sup	Range
Unsuited All Subjects	-61	35	95	-60	30	90
ACES Unpress	-65	79	144	-71	95	166
ACES Press	-116	101	217	-127	104	230
MK III Press	-90	99	189	-104	102	207
I-Suit Unpress	-94	111	205	-78	111	189
I-Suit Press	-117	106	223	-112	106	218
EM-ACES Unpress	-56	62	118	-68	93	161
EM-ACES Press	-75	103	178	-89	109	198

*All Units in Degrees

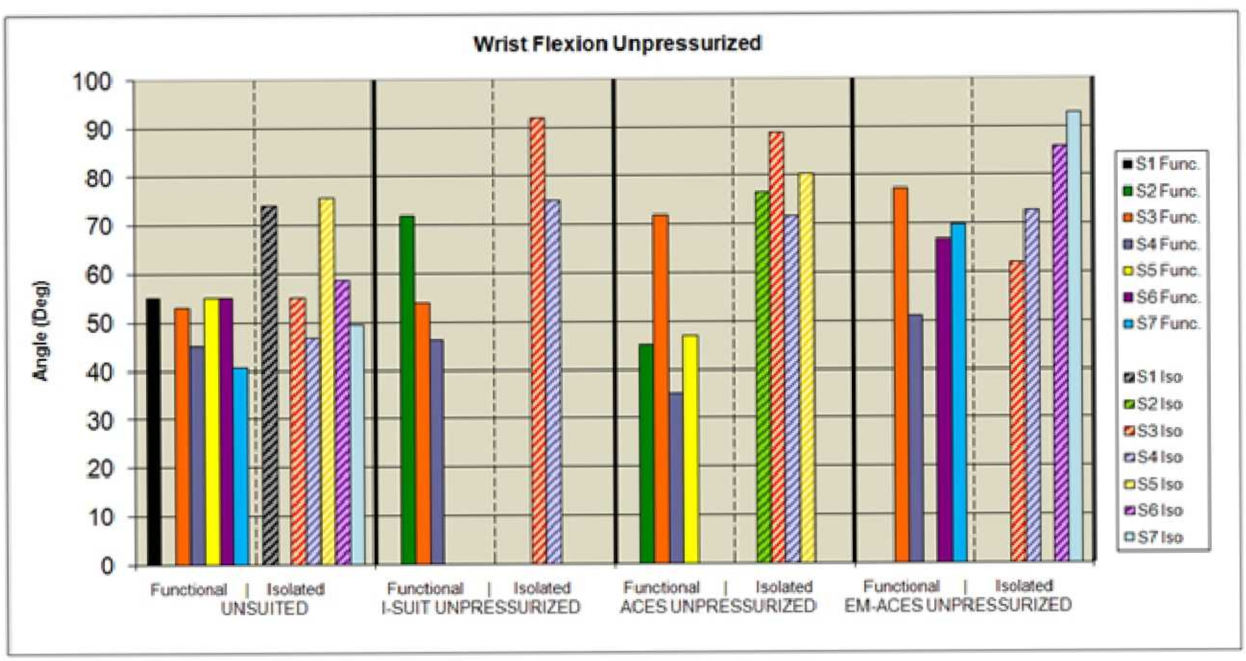


Figure 78: Wrist Flexion by Unpressurized Suit, Compared across Subjects

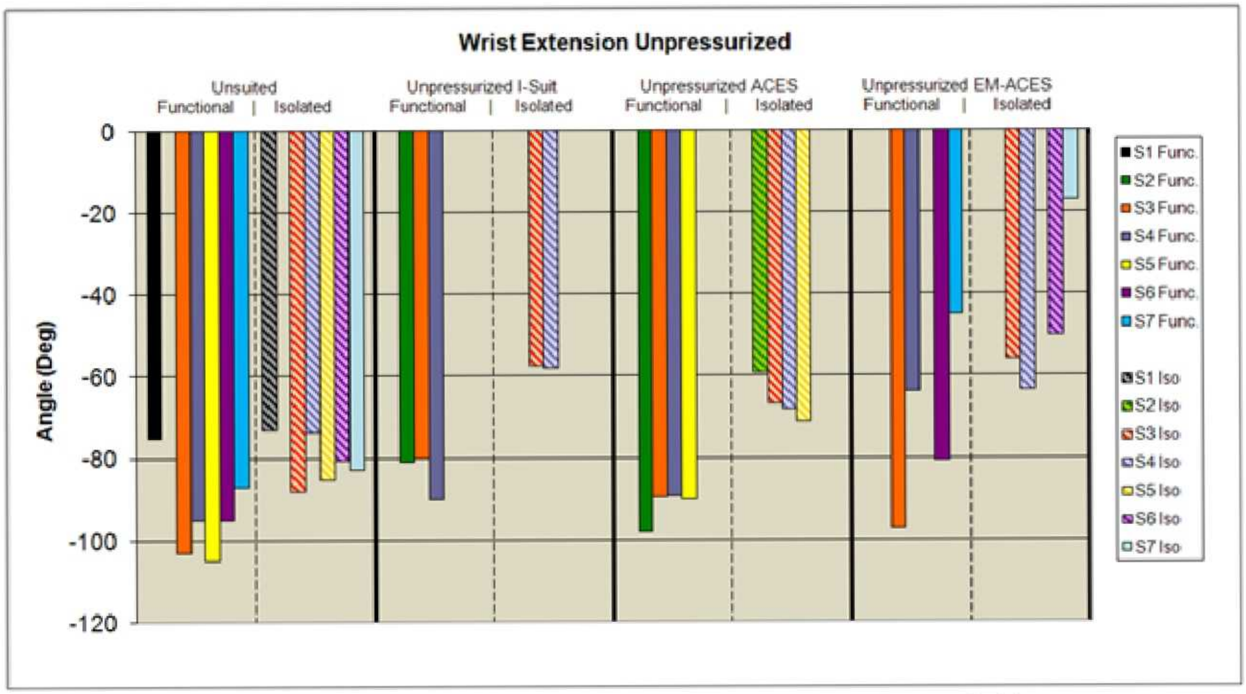


Figure 79: Wrist Extension by Unpressurized Suit, Compared across Subjects

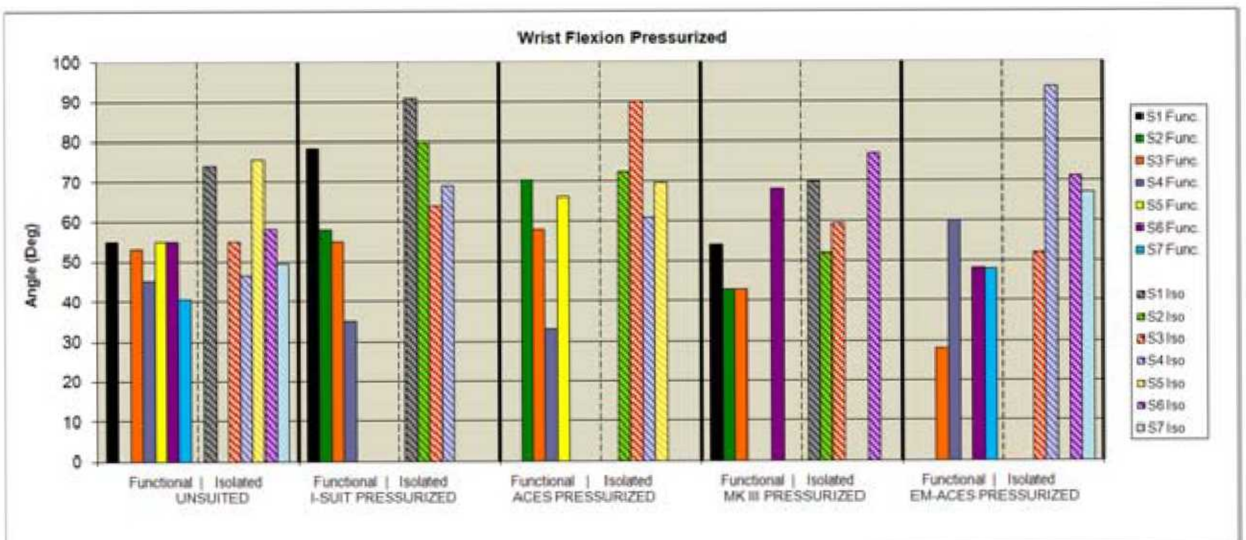


Figure 80: Wrist Flexion by Pressurized Suit, Compared across Subjects

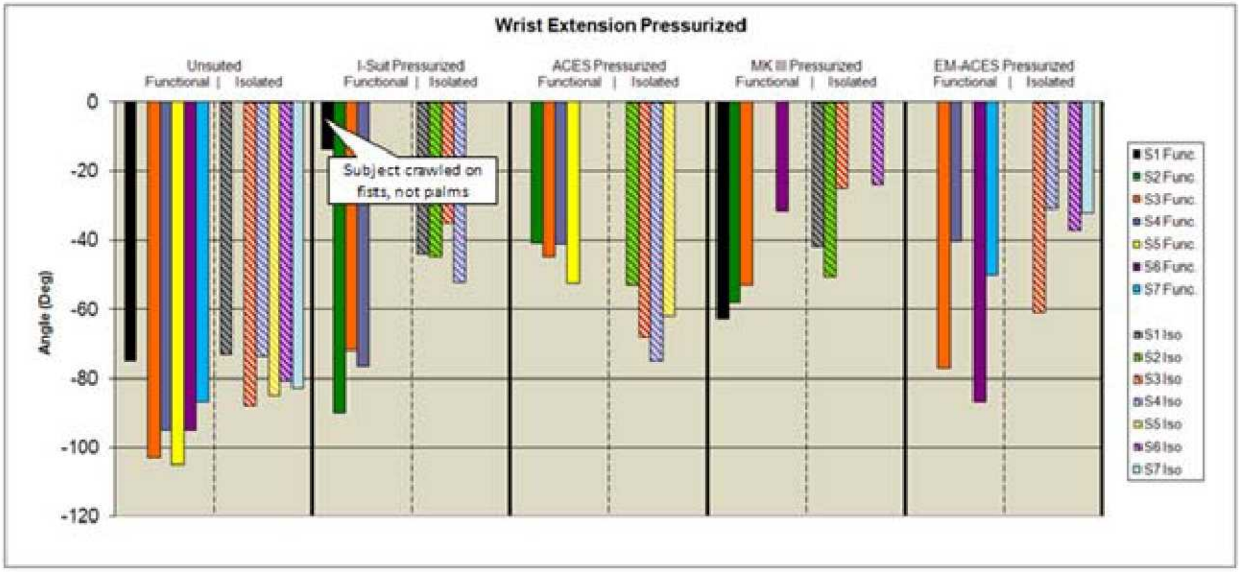


Figure 81: Wrist Extension by Pressurized Suit, Compared across Subjects

The Wrist

Because it was very difficult to distinguish anatomical landmarks while a subject was wearing pressurized gloves, suited wrist mobility values may sometimes be exaggerated. Also the type of gloves was not kept consistent across trials.

<u>Unsuited Wrist Flexion</u>

- Functional wrist flexion/extension was approximately equal to isolated wrist mobility, indicating that subjects used all that was available.

<u>ACES Wrist Flexion</u>

- For safety reasons associated with low mobility, subjects in the pressurized ACES never completed crawling or fall recovery trials, which normally maximized wrist extension in the I-suit and unsuited cases.

<u>MK III Wrist Flexion</u>

- For the most part, MK III subjects used a different style of crawling than they would have in the I-suit or when unsuited. They crawled on their elbows or on their knuckles, while I-suit subjects generally crawled on their palms (as seen in Figure 82). This may help explain why the MK III has a smaller average value for functional wrist extension than the I-suit, but a similar maximum flexion.

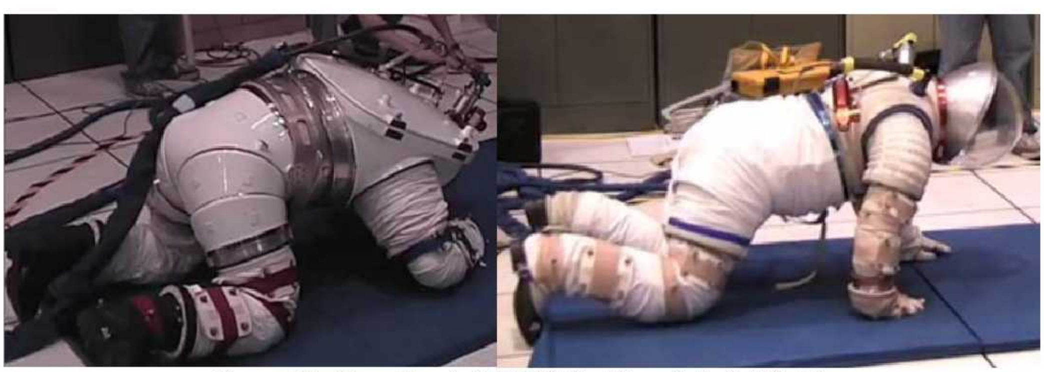


Figure 82: Crawling in MK III (Left) vs. I-Suit (Right)

I-Suit Wrist Flexion

- The average value for wrist extension in the I-suit is skewed downwards by one subject, who crawled on their knuckles instead of their palms. Several of the smaller subjects mentioned that their hands came completely out of the gloves as they were crawling, so this could have been an adaptation to this issue.

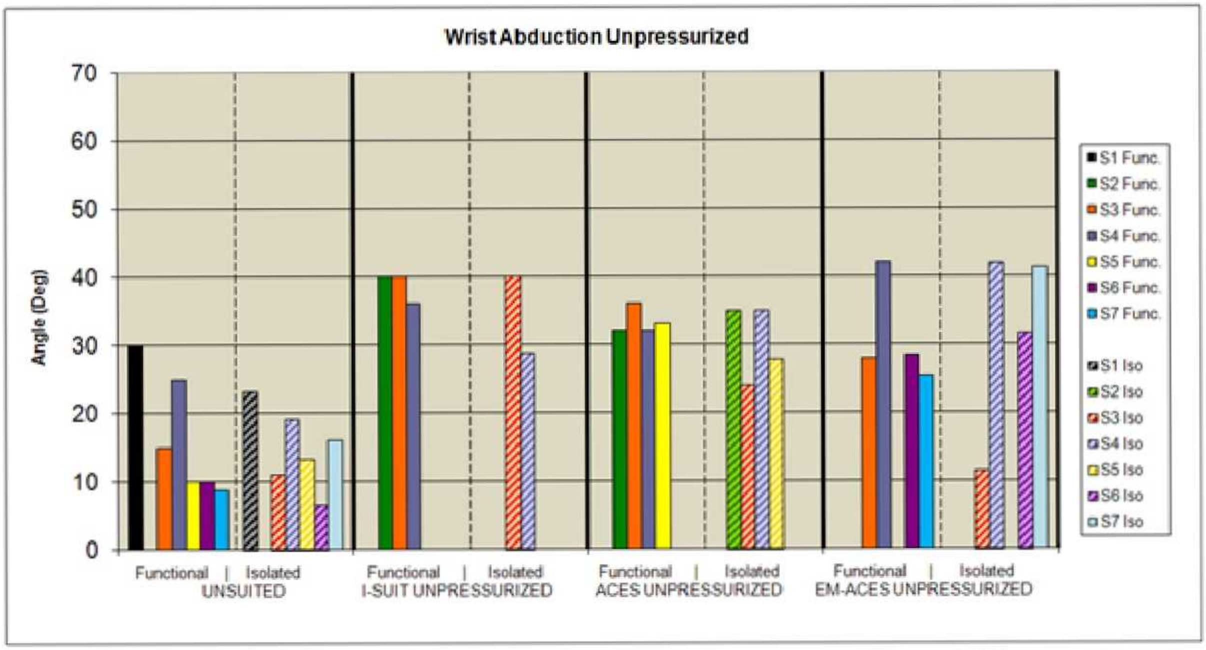


Figure 83: Wrist Abduction by Unpressurized Suit, Compared across Subjects

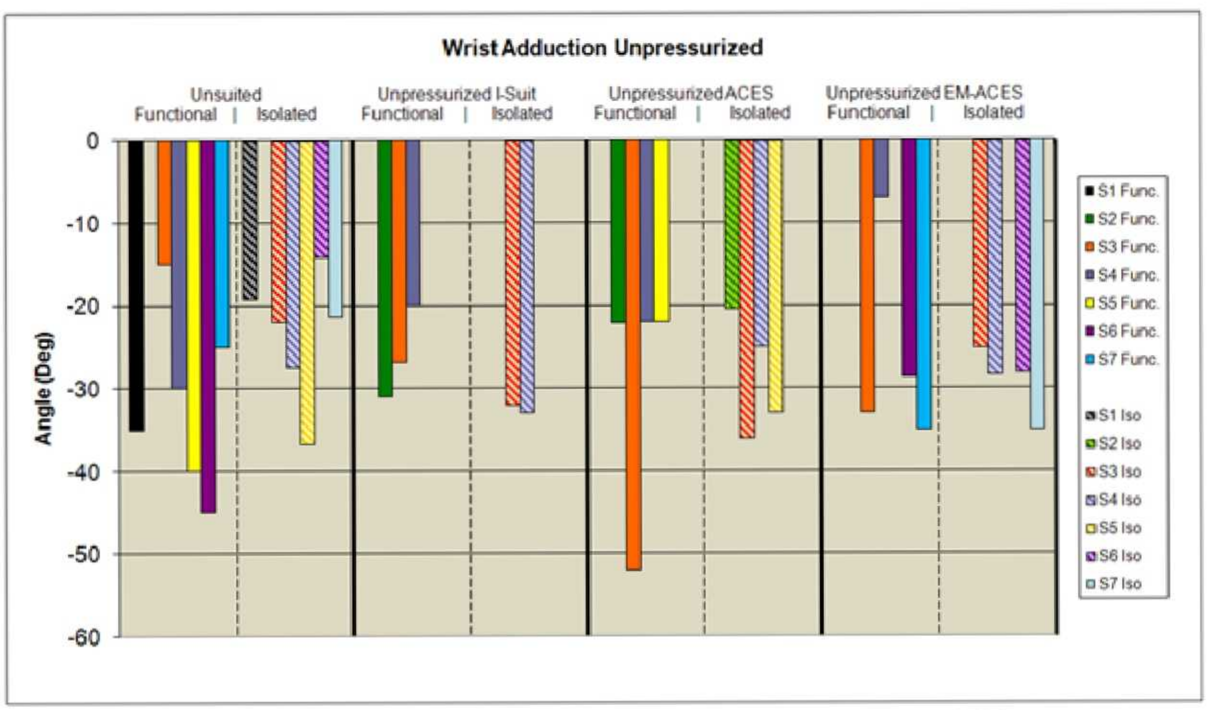


Figure 84: Wrist Adduction by Unpressurized Suit, Compared across Subjects

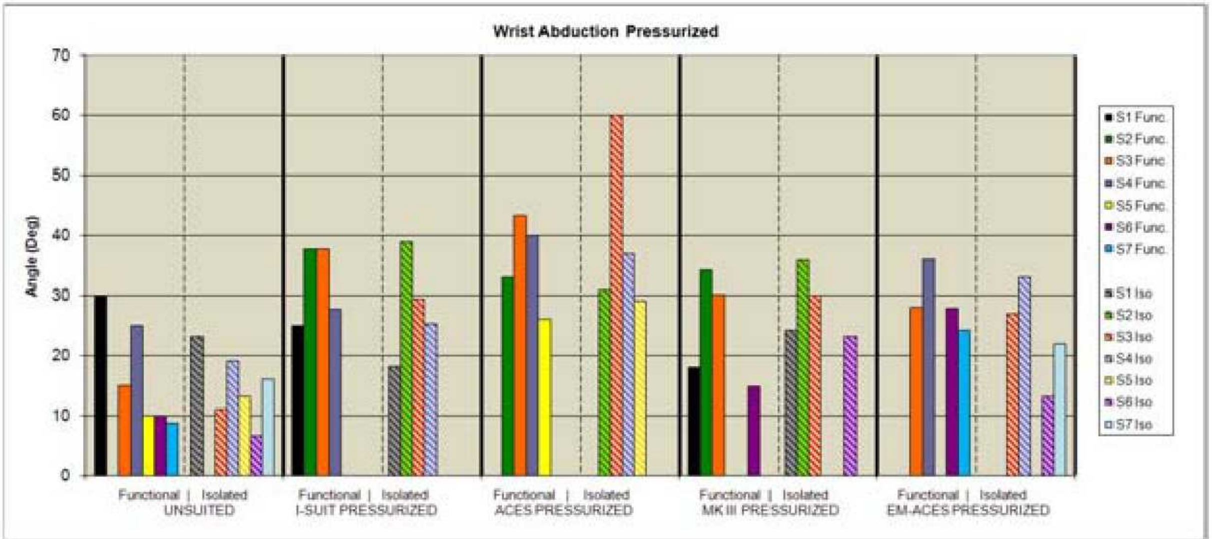


Figure 85: Wrist Abduction by Pressurized Suit, Compared across Subjects

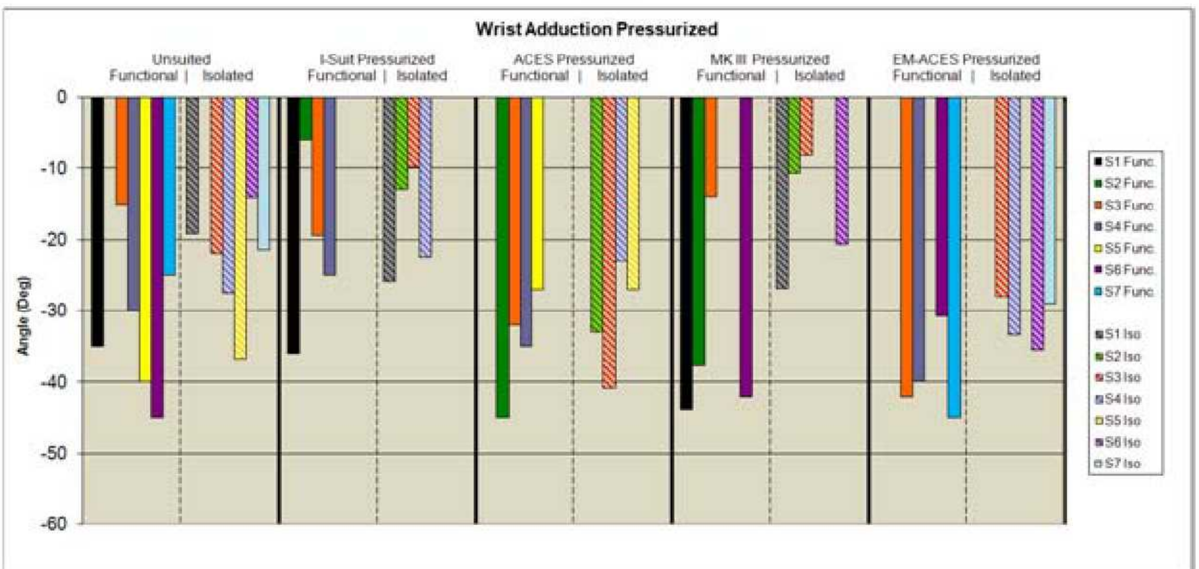


Figure 86: Wrist Adduction by Pressurized Suit, Compared across Subjects

<u>Unsuited Wrist Abduction</u>

- Functional wrist abduction/adduction was approximately equal to isolated wrist mobility, indicating that subjects used all that was available.

<u>ACES Wrist Abduction</u>

- The pressurized ACES seemed to have the highest wrist abduction/adduction range for all conditions and all suits, for both isolated and functional trials.

<u>MK III Wrist Abduction Adduction</u>

- The MK III had similar abduction/adduction mobility to the pressurized I-suit, in both the isolated and functional cases.

<u>I-Suit Wrist Abduction Adduction</u>

- I-suit wrist abduction and adduction value were comparable to unsuited, with a slight decrease in mobility when the suit was pressurized.

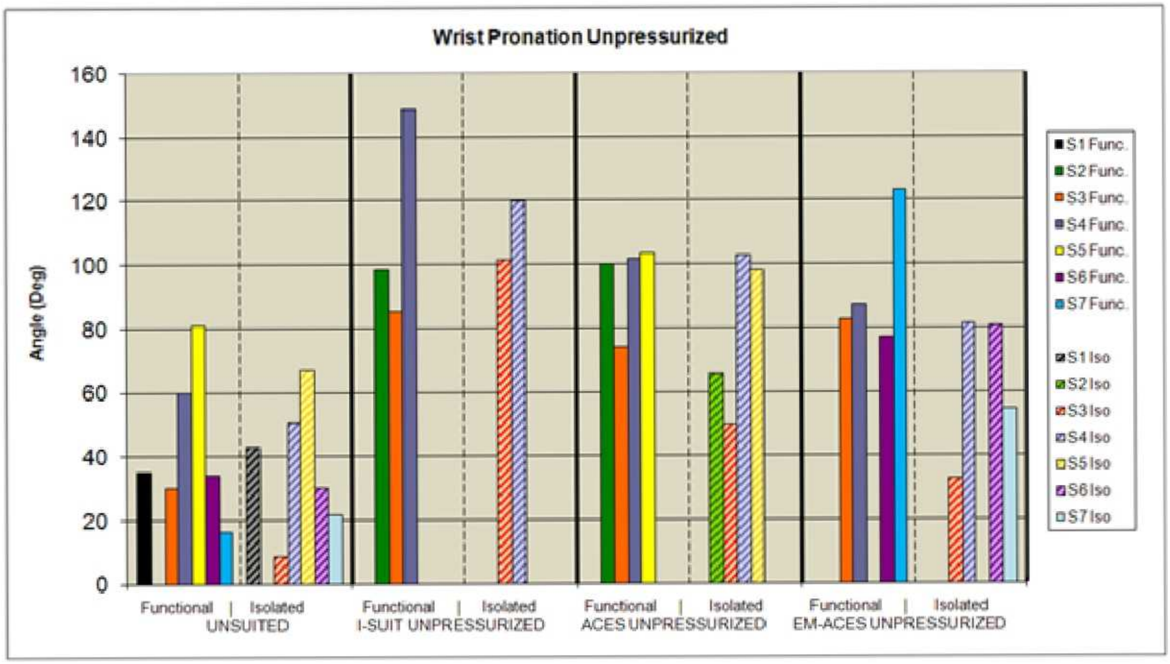


Figure 87: Wrist Pronation by Unpressurized Suit, Compared across Subjects

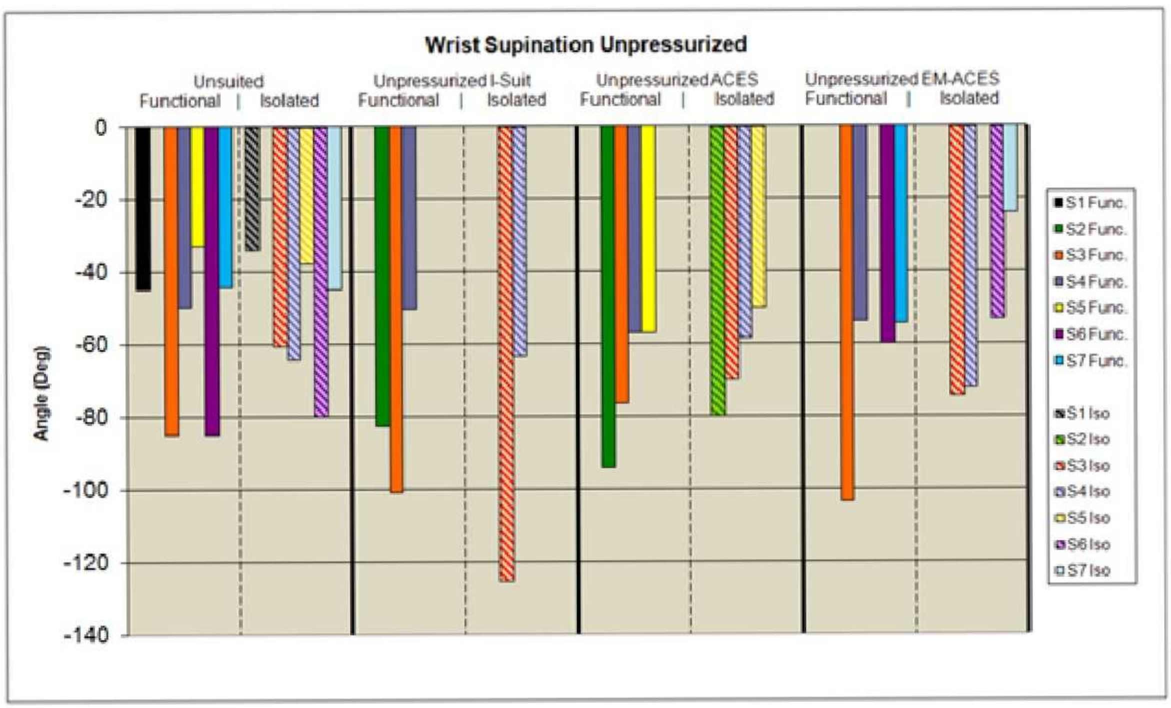


Figure 88: Wrist Supination by Unpressurized Suit, Compared across Subjects

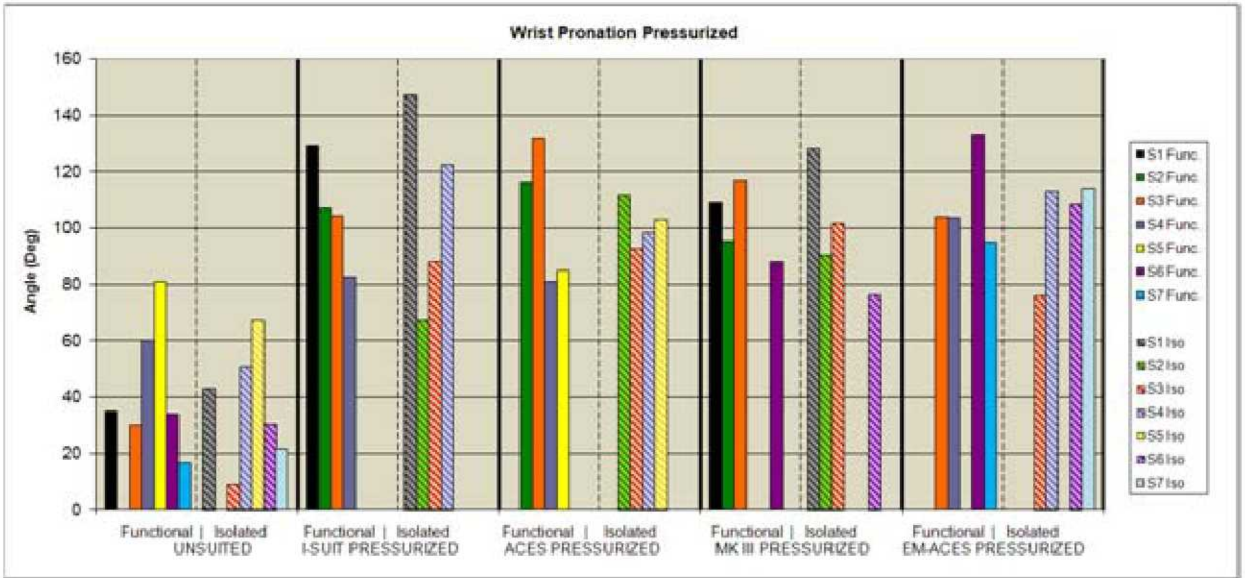


Figure 89: Wrist Pronation by Pressurized Suit, Compared across Subjects

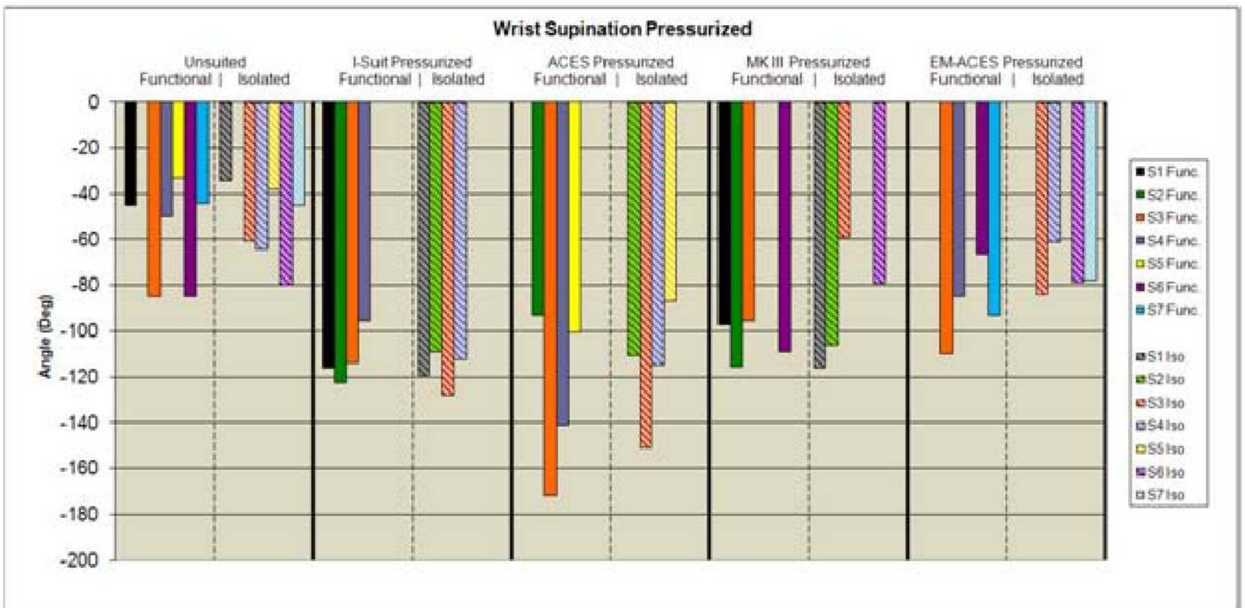


Figure 90: Wrist Supination by Pressurized Suit, Compared across Subjects

Unsuited Wrist Rotation

- Functional wrist rotation was approximately equal to isolated wrist rotation, indicating that subjects used all that was available.

Suited Wrist Rotation

- Because all the suits in this study incorporated wrist bearings, measured wrist rotation values were far higher than unsuited values. This phenomenon occurs because the bearing isolates the lower arm segment of the suit from the glove/hand segment, allowing free rotation. In the unsuited case, wrist and lower arm rotation are coupled resulting in markedly reduced apparent wrist rotation.

3.2 General Discussion

While the results of this testing can be useful for determining subtle aspects of suited mobility, care should be taken when comparing suited to unsuited mobility. Difficulties arise because different subjects were involved in each of the suited conditions, and not all of the subjects were involved in the original unsuited study, with its subject pool of 20 subjects. There were also differences in the methodology between suited and unsuited tests. For example, the list of functional tasks was altered slightly for some suited conditions in the interests of safety, as detailed in Appendix B. For instance, fall recovery was not attempted in the MK III or the pressurized ACES. Also, the intended application of the unsuited data led to calculation of the inter-subject mode, which was not feasible with the smaller subject pools involved in suited testing.

Caution should also be used when comparing mobility across suit architectures (as they are illustrated in Figure 91). As previously mentioned, the same subjects were not involved consistently in each suited condition, although generally three of the four were replicated. Suit fit was also not necessarily optimal because of a limited available range of sizing elements, and this was exacerbated for certain subjects outside the optimal operating range. Experience in the suits was not consistent across all subjects, which could potentially lead to variances in suited mobility. Also, the specific constraints of each suit led to tailoring of the functional task lists. For instance, because of mobility constraints and safety concerns, the task list for the pressurized ACES was pared down significantly compared to the other suited conditions. Testing in the EM-ACES was similarly limited, but with slightly more ambulation type trials attempted. For instance, crawling was performed in the EM-ACES but not attempted in the ACES. (Again, see APPENDIX B: Functional Tasks List and Descriptions for a complete breakdown of tasks).

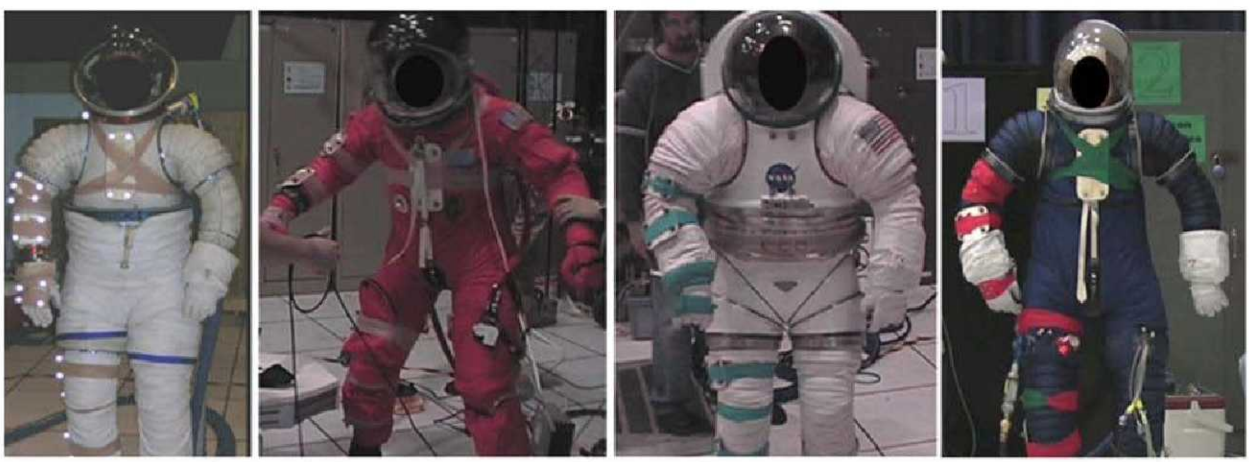


Figure 91: Space Suit Architectures: I-Suit, ACES, MK-III and EM-ACES

Because the ACES was designed for contingency operations and for a seated posture, no ambulation trials were attempted – in fact, mobility was so restricted, even upright seated trials were suboptimal (Figure 92). In order to safely reposition the subject in the recumbent seat, the suit was depressurized and brought back up to operating pressure in its new pose. One subject mentioned that strength was a factor when moving in the ACES – for instance, stronger subjects could force more air out of the suit and achieve higher values for torso flexion.


Figure 92: ACES Standing (Left) and Seated (Right) Posture

Attempts were made to place the EM-ACES in a seat, but the subjects were not stable in this posture. Instead, upright 'seated' reaches were completed with the subject standing. Due to similar issues with placing the subject in a recumbent seat, 'recumbent seated' trials were completed with the subject lying on a mat.


Figure 93: EM-ACES Attempts at Sitting

While four subjects performed both pressurized and unpressurized trials in the EM-ACES, only two of these subjects also completed the protocol in the ACES. These subjects had varying levels of experience in suits, and in particular, limited experience in the EM-ACES due to its recent delivery to NASA. There were also noticeable fit limitations for at least one subject, who mentioned that the suit was restricting his ability to lean forward at the waist. The same subject also had difficulty doffing the suit after the test.

Subjects may have been restricted in achieving the full mobility of the MK-III and the I-suit, due to aspects such as suit fit and the planetary suits' weight in the 1-g testing environment. For example, MK-III subjects seemed to have difficulty in completing tasks such as climbing a ladder or crawling, and did not even attempt the fall recovery trial. Similarly, only two of the four I-suit subjects successfully completed the fall recovery trial – although the restriction on the other two subjects may have been more a factor of suit size than weight. Smaller subjects reported having an excess of volume in the WEI-Suit torso, so that when they were crawling or attempting fall recovery trials, their hands were actually driven back out of the gloves. Also, the final three MK-III subjects did not complete any of the trials in the recumbent seat, due to safety concerns. This may be problematic, since some of the tasks that were normally performed in the recumbent position were historically found to maximize joint ranges of motion for other suits. In addition, two of the subjects used for quantifying the MK-III's mobility had never done an involved test in the MK-III.

Fatigue and/or discomfort also seemed to play a role, especially in the unpressurized I-suit. This suit has some limitations in the unpressurized case, since it was designed to be used pressurized, in which case the suit weight is offloaded from the subject. Most subjects took frequent breaks to relieve the weight of the scye bearings from their shoulders, and one subject did not complete the isolated test case due to shoulder discomfort. This subject noticeably altered their movement strategies as the test progressed, including lifting themselves up on their toes while reaching for a high handhold, as if to avoid flexing their shoulder. Subjects also mentioned discomfort related to the ankle of the pressurized ACES.

3.3 Limitations

There are several limitations with this study, which should be considered when reading this report. First of all, bilateral symmetry was assumed, leading to reflective markers being placed only on the right side of the body. This assumption greatly reduced both the amount of data to process and the time and complexity of data collection. Care was taken to minimize the effect of asymmetry on range of motion values, to prevent artificially low maximums from being recorded. For instance, if one functional task involved the subject kneeling on their right knee, the next task in the list involved them kneeling on their left knee. With these precautions, the assumption was considered justified.

Other limitations related to this study involve the degree to which the test subjects represent the total crewmember population. Limitations in suited availability led to a relatively small subject pool and subject inconsistencies between suited conditions. Due to restrictions of suit availability, subject availability and in one case, discomfort leading to early test termination, only one of the seven suited subjects completed all of the suited and unsuited conditions. However, the variability in subject size and suit experience should have provided a good cross section of suited mobility. Additional testing is warranted to further investigate the role of subject size and experience related to mobility in the suits. A larger subject pool would also enable better comparison of the suited data, initially collected using 4 subjects per condition, to the unsuited data from 24 subjects.

The fidelity of the performed functional tasks to actual operational concepts must be considered as well. Planned tasks for lunar missions have changed and/or been clarified over the duration of this project. Particularly complex or critical tasks may need to be reinvestigated with higher fidelity mock-ups once more final designs are established.

The fact that this study was completed in 1-g was an unavoidable limitation of this test. Investigations into the role of gravitational state may be warranted with more accurate mockups, possibly in the NBL or in a reduced gravity aircraft, e.g. the C9.

4. CONCLUSIONS

Meaningful and enforceable requirements are vital to the design of any system interacting with humans. Unsuited functional mobility testing revealed some interesting nuances of human movement including variances in mobility utilized when completing functional tasks as well as the impact of compound joint motions and the influence of joint loading on range of motion. Suited requirements must reflect the fact that altered movement strategies are utilized while wearing a space suit. Despite changes in mobility, the vast majority of functional tasks attempted were successfully completed by suited subjects in both pressurized and unpressurized states. The findings of the suited test will help in the establishment of a database of current suit mobility and aid designers in developing future suit architectures. This data will also feed into design guidelines for human system interfaces. However, as mentioned in the general discussion, care must be taken when utilizing this mobility data. There are subtleties involved in this testing that can influence application of the data. For instance, the suited subjects reached much higher values of shoulder flexion when in the recumbent position than they could achieve standing upright. Because this higher value is captured in the functional mobility achieved by the suit, a designer could erroneously place a switch in a location that a suited subject could not reach while standing upright. The best way to capture these details is to confer with the test conductors, who are available to discuss the finer points of this testing.

Improved methods for the creation of space suit design requirements should lead to improved suit performance while maintaining crewmember safety and reducing overall costs. Improved requirements data will also play a role in providing more meaningful design requirements for vehicle designers through the use of a common point of reference [4]. Additionally, by archiving the ROM data necessary to complete each functional task, it will be possible to evaluate any shortcomings of future suits or changes to any requirements by immediately being able to reference what tasks could no longer be accomplished with any reduction in mobility. This results in further savings of time and money in hardware development. Utilization of functional mobility methods could play a helpful role in both attaining data to enter into models and validating results obtained from modeling.

5. REFERENCES

1. Man-Systems Integration Standards. Lyndon B. Johnson Space Center, Houston, Texas, October 1995. NASA-STD-3000, Revision B.

2. Thornton, W, and Jackson, J. Anthropometric Study of Astronaut Candidates, 1979 to 1980, (Unpublished Data) NASA-JSC. SP-2-86L-064.

3. International Space Station Flight Crew Integration Standard. Lyndon B. Johnson Space Center, Houston, TX, June 2006. NASA-STD-3000/T SSP50005, Revision

4. Human Systems Integration Requirements. Lyndon B. Johnson Space Center, Houston, Texas, In Press. NASA-CXP70024.

5. Barter, James E., Irvin Emanuel and Bruce Truett. A Statistical Evaluation of Joint Range Data, WADC-TR-57-31, Wright Paterson Air Force Base, Ohio, August 1957.

6. Chaffin, Don B. Andersson, Gunnar B. and Bernard J. Martin. <u>Occupational Biomechanics.</u> 3rd Edition. John Wiley and Sons, New York New York. 1999.

7. Boone DC, Azen SP. "Normal Range of Motion of Joints in Male Subjects." J Bone Joint Surg Am 1979;61:756-9.

8. Department of Defense. *Handbook for Human Engineering Design Guidelines*. Military Handbook 759C (MIL-HDBK-759C)

9. Doriot, Nathalie and Xuguang Wang. "Effects of Age and Gender on Maximum Voluntary Range of Motion of the Upper Body Joints." Ergonomics, Volume 49, No. 3, 22 February 2006, 269-281.

10. Kachingwe, Aimie and Phillips, Beth J. "Inter- and Intrarater Reliability of a Back Range of Motion Instrument." Arch Phys Med Rehabil 2005;86:2347-53.

11. Yi-Wen Chang, et al. "Measurements of Range of Motion for the Spine in Normal Individuals Using Electromagnetic Tracking Device." American Society of Biomechanics Conference, San Diego, CA 2001.

12. Graziosi, D, and Lee, R. "I-Suit Advanced Spacesuit Design Improvements and Performance Testing" SAE International Conference on Environmental Systems, 03ICES-27, Vancouver, Canada, 2003.

13. Egstrom, Glen H., Bachrach, Arthur J., Wells, Morgan J. "Range of Motion Studies of Anti-Contaminant Diving Dress." OCEANS '85. Vol. 2, pp. 956-958. 1985.

14. O'Hearn, Brian E., Bensel, Carolyn K., Polcyn, Amy Fronduti. Biomechanical Analyses of Body Movement and Locomotion as Affected by Clothing and Footwear for Cold Weather Climates. U.S. Army Research, Natick Soldier Center. Report A852234, NATICK/TR-05/013, 2005.

15. Roebuck, John A. "A System of Notation and Measurement for Space Suit Mobility Evaluation." Human Factors, 1968, 10 (1), 79-94

16. Joseph F. Kubis et. al. “Apollo 16 Time and Motion Study.” http://history.nasa.gov/alsj/19730008098_1973008098.pdf

17. West, Philip R., Trausch, Stephanie V., “Performance Evaluation of Candidate Space Suit Elements for the Next Generation Orbital EMU,” 22nd International Conference on Environmental Systems, SAE Paper 921344 July, 1992.

18. Graziosi, David, Ferl, Janet G., “Performance Evaluations of an Advanced Space Suit Design for International Space Station and Planetary Applications.” 29th International Conference on Environmental Systems, SAE Paper July, 1999.

APPENDIX A: Full List of Considered Tasks

Mission Phase	Anticipated Activities	Tasks (Actions Involved in Completing Activities)
Prelaunch	• Don Suit • Ride in Van • Ingress Vehicle • Possible Abort	• Walk • Crawl • Sit • Climb Ramp/Ladder • Adjust Visor/Seatbelt/Controls • Stow Cargo • Emergency Egress/Evacuation • Zip Line
Launch	• Sit • Reach Controls • Adjust Visor	• Sit • Reach Controls • Adjust Visor
IVA	• Emergency Scenarios Requiring Suits	• Open Hatch • Manipulate Cargo • Walk • Crawl • Climb Ladder • Seat Ingress/Egress
EVA	• Egress Vehicle • Microgravity Locomotion • Reduced (Martian or Lunar) Gravity Locomotion • Perform Maintenance on Vehicle • Collect Rock/Soil Samples • Deploy Payload/Equipment • Habitat Fabrication • Fall Recovery • Drive Rover • Ingress Vehicle	• Open Hatch • Close Hatch • Walk • Run • Crawl • Kneel • Climb/Descend Ladder • Climb/Descend Ramp • Pull Along Tethers/Handrails • Jump • Fall Recovery • Sit • Activate Foot Pedals • Use Steering Wheel • Touch One or Both Hands to Ground • Lift a Box • Move a Box • Use Tools (Hammer, Wrench, Screwdriver, Shovel, Pick Axe, Drill, Camera, Bolt) • Brush Off Lunar Dust • Adjust Visor
Return/Reentry	• Reentry • Vehicle Egress • Raft Ingress • Emergency Abort	• Ingress Seat • Adjust Seatbelt/Straps • Egress Seat • Egress Vehicle • Ingress Raft • Pull Along Tether • Parachute • Air Slide

APPENDIX B: Functional Tasks List and Descriptions

Example: Task, (task trial name in data collection), Task description.

Functional Task	Unpressurized I-Suit	Pressurized I-Suit	Unpressurized ACES	Pressurized ACES	Pressurized MK III	Unpressurized EM-ACES	Pressurized EM-ACES
1. Walking: (Walk1, Walk2) Subjects walked at a self-selected pace across the capture volume. Data collection began outside the capture volume to allow subjects to reach steady state gait before reaching middle of capture volume.	YES	YES	YES	NO	YES	YES	YES
2. Kneeling: (Kneelrightknee, Kneelleftknee) Subjects began in a neutral, standing posture on a gym mat and slowly lowered themselves onto each knee in turn.	YES	YES Note: one subject fell forward while completing this motion. After this a stability aid (a PVC pipe) was used	YES	NO	YES Note: One subject's leg turned outward as they attempted to kneel	YES	YES
3. Crawling: (Crawl1, Crawl2) Subjects started on a gym mat on the edge of the capture volume. Subjects then crawled across the capture volume.	YES	YES Subject 1 crawled on their knuckles, the rest on their palms	YES	NO	YES Subjects crawled on knuckles or elbows, not palms	YES	YES
4. Prone-to-Standing: (Pushuptostand1, Pushuptostand2) Subject began the collection prone on a gym mat holding a pushup pose. Subject then rose from the pushup into a standing posture.	YES	Subjects 2 and 4 completed this trial. Others were likely hampered by poor fit, hands coming out of gloves	YES	NO	NO Not attempted in a 1-G condition	YES	NO
5. Hammering: (Hammerhigh, Hammershoulder, Hammerwaist, Hammerhighfast, Hammershoulderfast, hammerwaistfast) The subject hammered at the height and speed indicated. During the fast trials, they hammered more quickly than normal.	YES	YES	YES	YES	YES	YES	YES
6. Box Lift: (Boxliftbendknees, Boxliftbendwaist) Subject stood upright in the center of the capture volume with a standard milk crate on the floor in front of them. The subject then picked up the box and raised it to chest height. Unsuited subjects were instructed to perform this task once while bending primarily at the knees and a second time while bending primarily at the waist.	YES Suits completed only once, without attempting to isolated knees or pelvis	YES Suits completed only once, without attempting to isolated knees or pelvis	YES Suits completed only once, without attempting to isolated knees or pelvis	NO	YES Suits completed only once, without attempting to isolated knees or pelvis	YES Suits completed only once, without attempting to isolated knees or pelvis	YES Suits completed only once, without attempting to isolated knees or pelvis
7. Cargo Manipulation: (BoxtwistFtoR, BoxtwistFtoL, BoxtwistRtoL) Subjects stood in the center of the capture volume. Subjects then moved a milk crate from the starting point to the final point, resulting in approximately 90 degree rotations from front to right, front to left, or a 180 degree rotation from right to left.	YES	YES	YES	NO	YES	YES	YES

Functional Task	Unpressurized I-Suit	Pressurized I-Suit	Unpressurized ACES	Pressurized ACES	Pressurized MK III	Unpressurized EM-ACES	Pressurized EM-ACES
8. Ladder Climb: (Ladderforward, Ladderturnaround) Subjects started at one edge of the capture volume with a safety ladder in front of them. The subject climbed the first three steps of the ladder, paused, and then either climbed straight back down to the floor or carefully turned around on the third step and climbed back down to the floor facing forward.	YES	YES Pressurized Suits only took one step up, for safety	YES	NO	YES Pressurized Suits only took one step up, for safety Noted problems with ladder tipping due to suit weight	YES	YES Subjects only climbed one step, did not complete turn
9. Seated-to-Standing: (S2Sarmsside, S2Sarmsfront, S2Sarmsassist) Subjects began the task sitting on the edge of a chair in the center of the capture volume. Subjects then rose to a standing position while having their arms either directly in front of them, directly at their sides, or assist them into a rising position.	YES	YES	YES	NO	YES	YES	NO
10. Seated Toe Touch: (Seatedtoetouch) Subjects sat on the very edge of chair and leaned forward to just barely touch their toes with both hands.	YES	YES	YES	NO	YES Subject 2 could not bend at the waist while sitting	YES One subject struggled to bend at waist while sitting	NO
11. Upright Seated Reach: (SRabovehead, SRbehindhead, SRthumbreach, SRcontrashoulder) Subjects sat on the edge of a chair in the center of the capture volume. Subjects then performed four reaching tasks: reaching for a target above their heads, mimic raising and lowering the visor on a suit, reaching across their body with their arm parallel to the floor, and touching their left shoulder while keeping their elbow as low as possible	YES	YES	YES	YES	YES	YES	YES* Completed these trials standing up, since the suit could not be seated
12. Recumbent Seat Ingress: (RSingress) Subjects began the trial standing beside the recumbent seat. Subjects then sat in the seat getting into the proper recumbent seated position.	YES	NO Subject was assisted into the seat for safety	YES	NO Suit was depressurized, repressurized in seated posture	NO Subject was assisted into the seat for safety	YES	NO No testing in the recumbent seat, due to the suit's pressurized posture
13. Recumbent Seated Reach: (RSabovehead, RSbehindhead, RSthumbreach, RScontrashoulder, RSstrap) Subjects perform the same four tasks they performed in a seated position while now in a recumbent position. Subjects also performed an additional task where they reached over their shoulder to reach a strap for the five-point harness.	YES	YES	YES	YES	Only Subject 1 completed trials in the recumbent seat, due to safety concerns and interference with connectors on suit back	YES	YES* Could not ingress seat, completed these trials while lying on a mat
14. Recumbent Seat Egress: (RSegress) Subjects began the trial in the recumbent seat and then rose into a standing posture beside the recumbent seat.	YES	YES No subjects successfully completed this trial, but all attempted	YES	NO	Subject 1 attempted, but did not successfully complete this trial. No other subjects attempted.	YES	NO

Functional Task	Unpressurized I-Suit	Pressurized I-Suit	Unpressurized ACES	Pressurized ACES	Pressurized MK III	Unpressurized EM-ACES	Pressurized EM-ACES
15. Hatch Rotation: (Hatchrotationwheel, Hatchrotationladder) The Primus RS was placed on the edge of the capture volume and its work head was adjusted to be level with the subject's chest. The work head was fitted with the wheel or the ladder attachment, each in turn. The subjects then rotated the attachment a full rotation clockwise immediately followed by a full rotation counterclockwise. The wheel attachment was used to be representative of a traditional hatch while the ladder attachment represented the concept of replacing a wheel with a peg on a lever arm.	YES	YES	YES	YES One subject hit their helmet with the handle of the hatch, as it was rotating.	YES	YES	YES
16. Twist Tools: (Twistbolt, Twistwrench, Twistscrewdriver) The Primus RS was adjusted to be level with the subject's hand with the subject's elbow bent at 90 degrees. The subject then grasp each tool in turn and rotated it one full rotation clockwise followed immediately by one full rotation counterclockwise.	YES	YES	YES	YES	YES	YES	YES
17. Shoveling: (Shoveling) The Primus RS was fitted with its shoveling attachment and the work head was lowered until the subjects said it felt like they were shoveling at ground level. The subjects then swung the shovel attachment several times as though they were digging.	YES	YES	NO Not considered a micro-G task, so ACES did not complete	NO Not considered a micro-G task, so ACES did not complete	YES	YES 3 out of 4 subjects completed this task	NO Not considered a micro-G task, so pressurized EM-ACES did not complete
18. Foot Actuation: (Footactuation, Ankleflex) An adjustable chair was brought in so that the subject could sit with their right foot at the proper height to use the Primus RS with its pedal attachment. The subjects performed two tasks, first raising and lowering their foot as though stomping on a pedal. The second task featured the subjects primarily flexing and extending their ankle representing more subtle movements of a foot pedal.	YES	YES	YES	YES	YES	YES	YES
19. Hatch Manipulation: (Hatchpullup, Hatchrightleft, Hatchoverhead) The Primus RS work head was fitted with the ladder attachment for simulating a hatch again. The subjects first simulated pulling a hatch up that was below them. The work head was then raised to chest height and rotated so that the ladder attachment swung parallel to the floor. The subject then performed the 'Hatchrightleft' task simulating swinging a hatch open from side to side. The work head was then raised further so that the subject could simulate pulling down a hatch that was above head level.	YES	YES	YES	YES	YES	YES	YES

Functional Task	Unpressurized I-Suit	Pressurized I-Suit	Unpressurized ACES	Pressurized ACES	Pressurized MK III	Unpressurized EM-ACES	Pressurized EM-ACES
20. Tether Pull: (Tetheroverhead, Tetherhandoverhand) The Primus RS work head was fitted with the cable attachment and raised above head level. The subject then pulled the cable vertically downwards. The work head was then moved to chest height and the subject pulled the cable directly towards themselves.	YES	YES	YES	YES	YES	YES	YES
21. Ramp Climb: (Rampforward, Rampturnaround) An approximately 5 foot long ramp with a 20 degree incline was placed in the center of the capture volume. The subject began each trial outside the capture volume, walking into view and up the ramp. On the 'Rampforward' trial, subjects backed down the ramp after reaching the top. During the 'Rampturnaround' trial, subjects turned around after reaching the top of the ramp and descended the ramp facing forward.	YES	YES	YES	NO	YES	YES	YES
22. Recumbent Seat Ingress on Ground: (Chairtip) This trial was essentially identical to the 'RSingress' trial however for this trial a standard chair was laid on its back on a gym mat such that the subject had to ingress a recumbent seat that was flush with the floor.	NO High risk activity with high likelihood of marker occlusion, knocking markers off, damaging suit or harming subject	NO High risk activity with high likelihood of marker occlusion, knocking markers off, damaging suit or harming subject	YES	NO	NO High risk activity with high likelihood of marker occlusion, knocking markers off, damaging suit or harming subject	NO High risk activity with high likelihood of marker occlusion, knocking markers off, damaging suit or harming subject	NO High risk activity with high likelihood of marker occlusion, knocking markers off, damaging suit or harming subject

APPENDIX C: Maximum Unsuited Range of Motion by Task

Table 10: Maximum Shoulder Flexion by Task

Shoulder Flexion	
Trial Name	**# Maximized**
SRabovehead	10
Pushuptostand	3
RSabovehead	3
Hatchoverhead	3
Hammerhigh	1
Hammerhighfast	1
SRbehindhead	1
RSbehindhead	1
RSstrap	1

Table 11: Maximum Shoulder Extension by Task

Shoulder Extension	
Trial Name	**# Maximized**
Ladderturnaround	7
Chairtip	7
RSingress	5
RSegress	5

Table 12: Maximum Shoulder Adduction by Task

Shoulder Adduction	
Trial Name	**# Maximized**
SRcontrashoulder	10
Hatchrotationladder	4
BoxtwistFtoR	2
RScontrashoulder	2
BoxtwistFtoL	1
RSthumbreach	1
Hatchrotationwheel	1
Twistbolt	1
Twistscrewdriver	1
Shoveling	1

Table 13: Maximum Shoulder Abduction by Task

Shoulder Abduction	
Trial Name	**# Maximized**
SRbehindhead	5
Ladderforward	3
Ladderturnaround	3
Shoveling	3
RSingress	2
RSstrap	2
Hatchoverhead	2
Hammerhigh	1
Hammerhighfast	1
Hatchrightleft	1
Chairtip	1

Table 14: Maximum Elbow Flexion by Task

Elbow Flexion	
Trial Name	**# Maximized**
Shoveling	8
SRbehindhead	3
RSbehindhead	3
Hammerhigh	2
Ladderforward	2
Hammershoulder	1
SRthumbreach	1
RSstrap	1
RSegress	1
Hatchrightleft	1
Hatchoverhead	1

Table 15: Maximum Elbow Extension by Task

Elbow Extension	
Trial Name	**# Maximized**
Any Generic (neutral)	15
Walk	1
Pushuptostand	1
SRthumbreach	1
RSthumbreach	1
Tetheroverhead	1
Hatchoverhead	1
Rampturnaround	1
Rampforward	1
Chairtip	1

Table 16: Maximum Torso Right Lean by Task

Torso Right Lean	
Trial Name	**# Maximized**
Hammerwaistfast	10
BoxtwistFtoR	2
BoxtwistRtoL	2
Shoveling	2
Rampturnaround	2
Hammerwaist	1
Ladderturnaround	1
Twistscrewdriver	1
Tetherhandoverhand	1
Tetheroverhead	1
Rampforward	1

Table 17: Maximum Torso Left Lean by Task

Torso Left Lean	
Trial Name	**# Maximized**
Shoveling	7
BoxtwistFtoL	3
Rampturnaround	3
Walk	2
BoxtwistFtoR	2
BoxtwistRtoL	2
Hammerhigh	1
Hammerhighfast	1
Ladderforward	1
Hatchrotationwheel	1
Hatchoverhead	1

Table 18: Maximum Torso CCW Twist by Task

Torso CCW Twist	
Trial Name	**# Maximized**
BoxtwistRtoL	10
BoxtwistFtoL	5
Hatchrightleft	5
Hatchrotationladder	2
Hammerwaistfast	1
Tetherhandoverhand	1

Table 19: Maximum Torso CW Twist by Task

Torso CW Twist	
Trial Name	**# Maximized**
BoxtwistFtoR	9
BoxtwistRtoL	7
Hammerwaist	3
Walk	1
Pushuptostand	1
Hammerwaistfast	1
Ladderturnaround	1
Rampforward	1

Table 20: Maximum Torso Extension by Task

Torso Extension	
Trial Name	**# Maximized**
Walk	6
S2Sarmsassist	3
Hatchoverhead	3
Rampturnaround	3
Pushuptostand	2
Hammerhigh	2
Kneelrightknee	1
Hammerhighfast	1
Boxliftbendwaist	1
Ladderforward	1
Ladderturnaround	1

Table 21: Maximum Torso Flexion by Task

Torso Flexion	
Trial Name	**# Maximized**
Pushuptostand	18
RSingress	3
Seatedtoetouch	2
Crawl	1

Table 22: Maximum Knee Extension by Task

Knee Extension	
Trial Name	**# Maximized**
Any Generic (neutral)	9
Boxliftbendwaist	3
Walk	2
Tetherhandoverhand	2
Boxliftbendknees	1
BoxtwistFtoR	1
RSegress	1
Twistwrench	1
Shoveling	1
Tetheroverhead	1
Hatchpullup	1
Hatchoverhead	1

Table 23: Maximum Knee Flexion by Task

Knee Flexion	
Trial Name	**# Maximized**
Crawl	17
Boxliftbendknees	4
Kneelrightknee	2
Chairtip	1

Table 24: Maximum Hip Flexion by Task

Hip Flexion	
Trial Name	**# Maximized**
Pushuptostand	15
Seatedtoetouch	5
Crawl	1
RSingress	1
RSegress	1
Chairtip	1

Table 25: Maximum Hip Extension by Task

Hip Extension	
Trial Name	**# Maximized**
Walk	4
Rampturnaround	4
S2Sarmsassist	3
Hatchoverhead	3
Hammerhigh	2
Kneelrightknee	1
Kneellleftknee	1
Pushuptostand	1
Hammershoulder	1
Hammerhighfast	1
Boxliftbendknees	1
Ladderturnaround	1
Tetheroverhead	1

Table 26: Maximum Hip Adduction by Task

Hip Adduction	
Trial Name	**# Maximized**
Shoveling	8
BoxtwistFtoL	4
Ladderturnaround	4
Hammerhighfast	2
Hammerhigh	1
BoxtwistRtoL	1
Hatchrotationwheel	1
Tetheroverhead	1
Hatchoverhead	1
Rampturnaround	1

Table 27: Maximum Hip Abduction by Task

Hip Abduction	
Trial Name	**# Maximized**
Hammerwaistfast	12
BoxtwistRtoL	3
Walk	1
Kneellleftknee	1
Hammerwaist	1
BoxtwistFtoR	1
RSegress	1
Shoveling	1
Tetheroverhead	1
Rampforward	1

Table 28: Maximum Hip Internal Rotation by Task

Hip Internal Rotation	
Trial Name	**# Maximized**
BoxtwistRtoL	7
Hammerwaist	6
BoxtwistFtoR	5
Hammerwaistfast	2
Rampturnaround	2
Pushuptostand	1
Rampforward	1

Table 29: Maximum Hip External Rotation by Task

Hip External Rotation	
Trial Name	**# Maximized**
BoxtwistRtoL	7
BoxtwistFtoL	5
Hatchrightleft	3
Ladderturnaround	2
Hatchrotationladder	2
Hammerwaistfast	1
Shoveling	1
Hatchoverhead	1
Rampturnaround	1
Any Generic (neutral)	1

Table 30: Maximum Ankle Dorsiflexion by Task

Ankle Dorsiflexion	
Trial Name	**# Maximized**
Rampturnaround	6
Pushuptostand	5
Boxliftbendknees	5
Rampforward	3
Chairtip	3
BoxtwistFtoL	1
Hatchpullup	1

Table 31: Maximum Ankle Plantar Flexion by Task

Ankle Plantar Flexion	
Trial Name	**# Maximized**
Ladderturnaround	5
Crawl	3
RSingress	3
Footactuation	3
Ankle Flexion	3
Ladderforward	2
Rampturnaround	2
Pushuptostand	1
RSegress	1
Chairtip	1

Table 32: Maximum Wrist Flexion by Task

Wrist Flexion	
Trial Name	**# Maximized**
Ladderturnaround	2
RSingress	2
RSstrap	2
Hatchrotationwheel	2
Twistwrench	2
Chairtip	2
Hatchrotationladder	1
Tetherhandoverhand	1
Footactuation	1
Hatchoverhead	1

Table 33: Maximum Wrist Extension by Task

Wrist Extension	
Trial Name	**# Maximized**
RSingress	5
Crawl	3
Pushuptostand	2
RSegress	2
Chairtip	2
Hammerwaist	1
Ladderforward	1

Table 34: Maximum Wrist Adduction by Task

Wrist Adduction	
Trial Name	**# Maximized**
Twistwrench	2
Hammerwaistfast	1
Ladderforward	1
Ladderturnaround	1
SRabovehead	1
RSbehindhead	1
RSthumbreach	1
RScontrashoulder	1
RSstrap	1
Hatchrotationwheel	1
Hatchrotationladder	1
Shoveling	1
Tetherhandoverhand	1
Hatchrightleft	1
Hatchoverhead	1

Table 35: Maximum Wrist Abduction by Task

Wrist Abduction	
Trial Name	**# Maximized**
Twistscrewdriver	3
Hammershoulderfast	2
Ladderturnaround	2
Hammerwaist	1
Hammerwaistfast	1
Boxliftbendknees	1
Ladderforward	1
Hatchrotationladder	1
Shoveling	1
Tetherhandoverhand	1
Tetheroverhead	1
Chairtip	1

Table 36: Maximum Wrist Supination by Task

Wrist Supination	
Trial Name	**# Maximized**
Hatchrotationwheel	9
Twistwrench	3
Twistscrewdriver	3
RSegress	2
Hatchoverhead	2
Ladderturnaround	1
RSingress	1
Shoveling	1

Table 37: Maximum Wrist Pronation by Task

Wrist Pronation	
Trial Name	**# Maximized**
Twistscrewdriver	9
Hatchrotationladder	3
Twistbolt	3
Hammerwaistfast	2
Hatchrotationwheel	2
RSbehindhead	1
Twistwrench	1
Tetheroverhead	1